NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

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**RTO TECHNICAL REPORT** **TR-IST-052**

# Bridging the Gap in Military Robotics

(Combler le fossé existant dans le domaine de la robotique militaire)

Report on the Requirements and Gaps in Short-Term Military Robotics as identified during the IST-032 Workshop held in Bonn, Germany, September 2004.

Published November 2008

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# The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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# List of Abbreviations

| | |
|---|---|
| AT | Anti Tank |
| ATR | Automatic Target Recognition |
| | |
| BCM | Behaviour Co-ordination Mechanisms |
| | |
| C2 | Command and Control |
| COTS | Commercial Off-The-Shelf |
| | |
| DES | Discrete Event Systems |
| | |
| EMC | Electro Magnetic Compatibility |
| EOD | Explosive Ordnance Disposal |
| EURON | European Robotics Research Network |
| | |
| FPS | Frames Per Second |
| | |
| Gb | Gigabit |
| GIS | Geographical Information System |
| GPRS | General Packet Radio Service |
| GSM | Global System for Mobile communications |
| | |
| HF | High Frequency |
| | |
| IDS | Intrusion Detection/prevention System |
| IFF | Identification Friend or Foe |
| IP | Internet Protocol |
| ISR | Intelligence gathering, Surveillance and Recognition |
| IST | Information Systems and Technology |
| ISTAR | Intelligence, Surveillance, Target Acquisition and Reconnaissance |
| | |
| LF | Low Frequency |
| LoS | Line of Sight |
| | |
| MANET | Mobile Ad-hoc Networks |
| Mb | Megabit |
| MP | Mission Planning |
| MRS | Multi-Robot System |
| | |
| NATO | North Atlantic Treaty Organisation |
| NBC | Nuclear, Biological and Chemical |
| | |
| OS | Operating System |
| OSI | Open Systems Interconnection |
| | |
| PP | Path Planning |
| | |
| QoS | Quality of Service |

| | |
|---|---|
| R&D | Research and Development |
| RPG | Rocket Propelled Grenade |
| RTG | Research and Technology Group |
| Satcom | Satellite Communication |
| SDR | Software Defined Radio |
| TRL | Technology Readiness Levels |
| UAV | Uninhabited Aerial Vehicle |
| UGV | Uninhabited Ground Vehicle |
| UHF | Ultra High Frequency |
| UXO | Unexploded Ordnance |
| VFIR | Very-Fast-Infrared |
| VHF | Very High Frequency |
| WLAN | Wireless Local Area Network |

# List of Authors

Following is the list of authors that contributed to this white paper.


| Name | Role | E-mail |
|---|---|---|
| F.E. Schneider | Section coordinator | Frank.Schneider@fgan.de |
| R. Granot | Section coordinator | rgranot@inter.net.il |
| J. Roning | Co-author | Juha.Roning@oulu.fi |
| A. Winfield | Section coordinator | Alan.Winfield@uwe.ac.uk |
| E.J.A. van Zijderveld | Co-author | Erik.vanZijderveld@tno.nl |
| L. Walle | Co-author | laurent.walle@cybernetix.fr |
| E. Colon | Section coordinator | Eric.Colon@rma.ac.be |
| K. Pink | Section coordinator | kpink1@QinetiQ.com |
| R. Castelli | Co-author | castelli@macroswiss.com |
| D. Krogmann | Section coordinator | Dirk.Krogmann@diehl-bgt-defence.de |


Details on the Core Group and its activities can be found on the website http://www.european-robotics.org.

# Bridging the Gap in Military Robotics

## (RTO-TR-IST-052)

# Executive Summary


There appears to exist a gap between the ideas of the military on the use of ground robotics for their purposes and the technical possibilities offered by industry and research. In many cases the military are offered robots created by industry, but to a lesser degree robots developed to explicitly meet military needs.

To bridge this gap, a NATO workshop was organised September 2004 in Bonn, attended by over 70 participants from the military, industry, research and ministries from 16 different mainly European countries. The starting point for the workshop was defining the tasks for which the military would most like to use robots by the year 2008, including the functional requirements. In parallel, the industry and researchers defined the current status of robotics technology and the level of technology that is expected to be achieved by the year 2008 at the current rate of technology development.

Based on the differences between military needs on one hand and the expected level of technology by 2008 on the other hand, roadmaps were constructed. These roadmaps identify which actions should be taken in order to achieve the required level of technology by 2008, if at all possible. They also identify who should take action and how this should be organised.

It was recognised during the workshop that this is the first time that this type of analysis on the gap between user requirements and technical possibilities has been attempted.

In order to continue this process of interaction, a so-called Core Group was formed during the workshop. This Core Group continues the work of closing the gap between users and industry / researchers. One of the main activities of this Core Group, in pursuit of this goal, is the organisation of a European military robotics Capability Show in the second quarter of 2006. Details on the Core Group and its activities can be found on the website http://www.european-robotics.org.

# Combler le fossé existant dans le domaine de la robotique militaire

## (RTO-TR-IST-052)

## Synthèse


Un fossé semble exister entre les idées qu'ont les militaires sur l'emploi de la robotique terrestre pour répondre à leurs besoins et les possibilités techniques offertes par l'industrie et la recherche. L'armée se voit fréquemment proposer des robots créés par l'industrie, mais plus rarement des robots développés pour répondre spécifiquement aux besoins militaires.

Afin de combler ce fossé, l'OTAN a organisé un atelier en septembre 2004 à Bonn, auquel ont assisté plus de 70 participants issus de l'armée, de l'industrie, de la recherche et de divers ministères, en provenance de 16 pays majoritairement européens. Le point de départ de cet atelier fut la définition des tâches pour lesquelles les militaires souhaiteraient le plus pouvoir faire appel à des robots d'ici 2008, en incluant les exigences fonctionnelles. Parallèlement, les industriels et les chercheurs ont défini la situation de la technologie robotique à l'heure actuelle et le niveau technologique qu'ils prévoient d'atteindre en 2008, compte tenu du présent rythme de développement technologique.

En se basant sur les différences existant entre les besoins militaires d'un côté, et le niveau technologique prévu d'ici 2008 de l'autre, des feuilles de route ont été établies. Ces feuilles de route identifient les mesures à prendre en vue d'atteindre le niveau technologique requis d'ici l'année 2008, lorsque cela est possible. Elles définissent également qui doit prendre ces mesures et la manière dont cela doit être organisé.

Il a été reconnu lors de cet atelier que ce type d'analyse sur le fossé existant entre les exigences des utilisateurs et les possibilités techniques constituait une première.

Afin de poursuivre ce processus d'interaction, un groupe appelé Groupe principal a été formé au cours de cet atelier. Ce Groupe principal continue d'œuvrer pour combler le fossé entre les utilisateurs et l'industrie ou la recherche. L'une des activités majeures de ce Groupe principal, conformément à son objectif, est l'organisation d'une manifestation de démonstration des capacités robotiques militaires européennes pour le deuxième trimestre 2006. Les informations détaillées sur le Groupe principal et ses activités peuvent être consultées sur le site http://www.european-robotics.org.

# Chapter 1 – RATIONALE FOR A NATO WORKSHOP ON SHORT-TERM REALIZABLE MILITARY ROBOTS

In military robotics industry plays an important role. Not just for the simple reason that industry produces the robots, but also that industry has a more or less leading role in defining the military use of robotics. Just think of the way iRobot machines were introduced in Afghanistan. More or less standard robots were introduced into military operations without very thoroughly defined military functional requirements. The chosen approach was to test how these standard robots would function in an operational military environment.

This example is illustrative of a large part of robotic development for the military. Although there is of course some influence by the military on the robots' functionalities, the industry's capabilities and ideas on solutions are leading in most robotic projects. It is the opinion of NATO working group IST-032/RTG-014[1], this is an unsatisfactory situation that needs addressing.

Therefore, the NATO working group IST-032/RTG-014 organized a workshop to bring together military users, industry and researchers. The main goal of the workshop was to provide industry and researchers with a better understanding of the needs and desires for supporting robots, and at the same time give the military a better insight into technological possibilities and current limitations in robotics. The workshop also provided an opportunity for industry and researchers to ascertain different opinions amongst themselves on the current level of technological readiness. A final outcome of the workshop would be a roadmap, indicating what gaps are predicted to exist in the year 2008 between military user requirements for robotics and industrial robotic capabilities, what actions should be taken to close those gaps in time, and who should take action.

In short, the workshop was set up to bridge the gap on robotics between military users, industry and researchers.

[1] Named "Multi-robot systems in military domains". For the workshop, the working group decided not to put much emphasis on the multi-aspect but primarily focus on single robots instead, because of the quite short time horizon of the workshop that looked into robots being available in the year 2008.

# Chapter 2 – WORKSHOP SET-UP

The aim of the workshop was to find the gaps between military requirements and industrial capabilities in the field of robotics that will have to be closed to obtain usable military robots by the year 2008.

To achieve this aim, the workshop was organized according to the schedule shown in the figure below.

| | | | |
|---|---|---|---|
| Day 1 | Morning | Military define relevant tasks | Technicians define current technological status |
| | Afternoon | Military define operational requirements | Technicians define expected technological status by 2008 under current development speed |
| Day 2 | Morning | Military and technicians together match operational requirements and expected technological status by 2008 under current development speed | |
| | Afternoon | Military and technicians together construct roadmaps to close essential gaps between operational requirements and expected technological status by 2008 under current development speed | |
| Day 3 | Morning | Military and technicians together refine roadmaps | |
| | Afternoon | Military and technicians together present and discuss roadmaps | |

**Figure 2-1: Set-up of the Workshop.**

Also refer to Figure 2-2 below for a schematic overview of this approach, indicating the split between military and technicians in the beginning of the workshop and the joining of both groups from the second day on. Also note the military scenarios being fed into the technician's groups midway the first day.

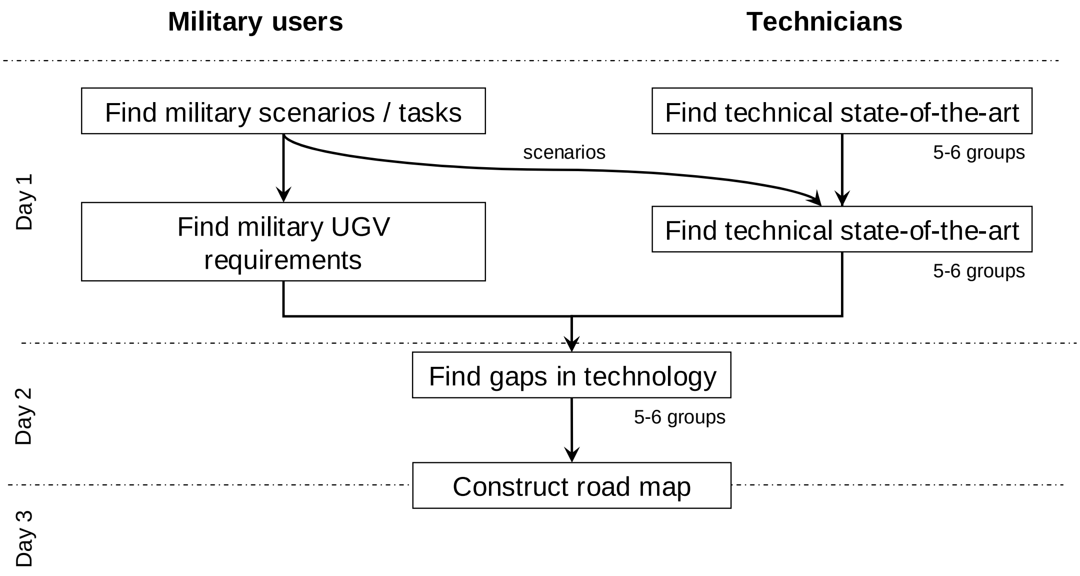


**Figure 2-2: Schematic View on the Workshop Set-up.**

## 2.1 FIRST DAY

During the first day the military were separated from the industry and researchers, so separated from the technicians. During the morning the military generated tasks for which they thought robotic support could be of some value. They also voted on the degree to which support by robots would be valuable to each of these tasks. Based on this voting the military selected the five tasks for which they felt robotic support would bring best value. During the afternoon, the military established the operational requirements for those five most valuable military tasks to be supported by robots.

During that same first day, the technicians were split into six groups for different fields of technological interest. These six fields were:

- Communication;
- Robot platforms;
- Sensing and world modelling;
- Navigation and mission planning;
- Human-robot interaction; and
- Multi-robot systems.

In the morning of that first day, the technicians established the current level of readiness for their field of technological interest. Each field of technological interest was split into numerous aspects that could easily be scored on the level of readiness and also used by the military to formulate their operational requirements. The levels of readiness were expressed in Technology Readiness Level (TRL) codes as shown in Annex A. During lunch break, the five relevant tasks as defined that morning by the users were fed into the six technical groups in order to give them a first and preliminary understanding of the user's preferences. During the afternoon of the first day, the technicians established the level that they expect to achieve by the year 2008 under the current, unchanged technological development speed.

## 2.2 SECOND DAY

On the second day, the military users were intermixed with the six technological groups. Together with the technicians, they matched their operational requirements for each of the five tasks against the level that the technicians had predicted they expect to achieve by the year 2008 under the current technological development speed.

Based on this matching process, for each of the six groups the most important technological issues were established. These were the issues that have a high relevance for many or all of the five military tasks, and at the same time are considered by the technicians to be at too low a level in the year 2008 taking into account the current technological development speed. In fact, these issues being of high user importance but of low technological feasibility by 2008 are the actual 'gaps' to close for a highly usable military robot.

For these 'gaps' the technological groups drafted roadmaps together with the military users. Essential for these roadmaps is of course the identification of the technical issues that need to be solved, but even more the way this should be done, who should take action and which interrelations with other technical issues (possibly from a different field of interest) exist.

## 2.3 THIRD DAY

In the morning of the third day, the six groups refined their roadmaps and prepared presentations on those results. In the afternoon the results were discussed, giving the groups good opportunity to exchange

information. Parts of these discussions were on how to proceed with the results of the workshop, and of course whether there was any need at all to proceed with these results.

The workshop was attended by about 70 people from the military, industry, research and government from 16 mainly European countries.

# Chapter 3 – MILITARY TASKS AND USER REQUIREMENTS

The military users generated a large number of tasks that might or might not be supported by robots. A total list of these tasks can be found in Annex B, but the five most relevant tasks according to the military are described in more detail here. These tasks were:

1) Reconnaissance and surveillance for tactical support of the forces on the ground including NBC (nuclear, biological, chemical).
2) De-mining; tactical and post-conflict - clearing roads and fields from AP (anti-personnel) and AT (anti-tank) mines.
3) Convoying; transport of goods.
4) Checking vehicles and people for explosives and weapons at checkpoints.
5) Carry equipment for dismounted soldier.

For each of these tasks the main purpose and user requirements are described in following sections. More detailed information on user requirements can be obtained from Annex B.

## 3.1 RECONNAISSANCE AND SURVEILLANCE FOR TACTICAL SUPPORT FOR THE FORCES ON THE GROUND INCLUDING NBC

In this task, the users envisage to use a single UGV (Unmanned Ground Vehicle) for zone, area, route and point reconnaissance. This means that the UGV should be fit for the following purposes:

- Tactical reconnaissance for short distance (about 100 meters);
- Tactical reconnaissance for wide areas;
- Tactical reconnaissance on routes;
- Inspection inside buildings;
- Inspection inside sewers; and
- Securing areas and objects (like buildings).

By combining these various activities in an UGV, the users try to explicitly indicate that they would prefer an UGV that can be used in multiple settings. This reduces the number of specialized UGVs as well as the number of specialized personnel to transport, operate and maintain the UGV.

When the users deploy an UGV like this, they need several outcomes or benefits from it. During the workshop, the users mentioned the following desired results when using the UGV:

- Information on location and movement (direction and speeds) of persons (civil and military) and vehicles (civil and military); this information should also include as much as possible an IFF (Identification Friend or Foe) indication;
- Information on NBC contaminated locations, meaning the type of contamination but also local meteorological information like wind speed and direction;
- Map information on routes. This should include the state of the route, buildings around the route and traffic density; and
- Warnings to the operator when a threat for an area of responsibility is detected.

As this type of UGV will be used in a variety of environments, it should be useable under all weather conditions, in all climates and in all sorts of terrain. The operational terrain for such an UGV is expected to include roads (concrete, tarmac, dirt or unpaved), urban environment (streets or buildings – both damaged and undamaged), fields, forests and even mountains. The UGV should optionally look for as much cover as possible; the operator should also be able to send it in a straight line to a specified location, without looking for cover.

For reliable enough information, this sort of UGV is likely to merge information from various sensors and vehicles. And in order to give the right amount of information without overloading the operator, the UGV should give the operator only information when relevant – this requires an intelligent assistance function, but also the possibility for the operator to get full sensor information on request. The UGV must be able to communicate with other manned or unmanned vehicles to point targets.

Very important in really assisting the operator would be the ability for the UGV to identify persons and vehicles with high reliability.

The UGV is threatened by all kinds of hostile fire (small calibres and tanks) which the UGV should be able to survive by virtue of its armour. The UGV is also threatened by fire, people stealing a small robot, mines and collisions. It should be able to erase its own computer or data, or it should be able to destroy itself if capture is eminent.

The UGV should be able to continue its mission as well as it is able when communication is (partly) lost; so a ‘graceful’ loss of function when the communication fails is desired.

## 3.2 DE-MINING – TACTICAL AND POST-CONFLICT – CLEARING ROADS AND FIELDS FROM AP AND AT MINES

Like the reconnaissance UGV, the users envisage to combine different types of de-mining that are currently distinct disciplines in the de-mining UGV. Tactical and post-conflict de-mining especially have quite different requirements in de-mining speed and de-mining accuracy. While tactical de-mining requires relatively high speed and accepts some mines not being detected, in post-conflict de-mining speed is not a great issue but a very high detection rate is crucial.

The operator specifies the area to search to the UGV. This can be either an already found mine field specified in coordinates, or it can be a region on a map. This area could also be a lane to clear.

This UGV should be capable of detecting mines and optionally (i.e. if the operator desires it) marking the mines. Wherever possible, the UGV should either remove the mine or disarm it in place. When a mine is found, the UGV should warn the operator and also provide the mine’s location and type, as well as the estimated time and success rate to clear the mine. Optionally, the UGV should inform the operator when the mine is marked or disarmed. It should be possible to operate the UGV both in a tele-operated and in an autonomous mode when clearing the assigned area or route.

As this type of UGV is to be used both for tactical and post-conflict de-mining, it should be usable on all kinds of roads, both roads in urban areas and in the fields. So this includes concrete roads, tarmac roads, trails and unpaved roads that can be either damaged or undamaged. The UGV should also be usable in all kinds of fields (hills, mountains, forests) as well as in urban terrain. The UGV should operate under all climates and weather conditions.

The UGV needs to find all types of AP and AT mines, buried and on-surface and about 10 meters off-route. The UGV should be able to receive and use airborne information on possible mine locations, for instance from UAVs flying over the area of operation.

The UGV should be able to operate under hostile fire (at least indirect fire such as mortars).

## 3.3 CONVOYING – TRANSPORT OF GOODS

This UGV should be able to transport the goods in an adequate time, meaning in the time a human driver would take. These goods can be palletized or ISO 20 feet containerized. The UGV should be capable of automated loading and unloading. It is acceptable if this automatic loading and unloading is done by one or more specialized UGVs in the convoy.

Highly important is the capability of this type of UGV to mix with normal traffic, thus it is important to address all legal issues that would follow.

It should be able to drive around major obstacles on the route, for instance a broken down vehicle. To the users, an acceptable solution would be a leader-follower vehicle concept, so only a limited number of intelligent UGVs leading the convoy and a proper number (ratio) of dumber UGVs just following the intelligent one.

The location of the convoy should be known at all times. The UGV must be able to follow a linked, man driven vehicle and it must also be able to move autonomously. The operator should be able to take control at any time.

## 3.4 CHECKING VEHICLES AND PEOPLE FOR EXPLOSIVES AND WEAPONS AT CHECKPOINTS

This UGV should approach a suspected vehicle or person and search for weapons and explosives. When found, the UGV should alert the operator and keep the vehicle and person from moving away. The UGV should be able to shield off an explosion from its own forces or buildings. It should also be able to identify the type of explosive and alert all persons in the vicinity on the presence of the explosives.

The typical working environment for this UGV is at a checkpoint, meaning that it is to be operated on a road (trail, gravel, tarmac or concrete).

For optimal usability, the UGV should memorize cars and persons spotted at the checkpoint for analysis later on. This information can be used for instance to establish certain cars crossing the checkpoint very often. The UGV should be able to communicate to give information on suspected persons and cars, but also on persons and cars already checked thus preventing them from being checked anew at the next checkpoint.

## 3.5 CARRY EQUIPMENT FOR DISMOUNTED SOLDIER

This UGV is meant to carry the equipment and supplies of a small number of soldiers. Therefore, the UGV must be able to follow the soldiers almost anywhere they go (except for swimming). It should also be usable for transportation of wounded soldiers.

As the UGV is to follow the soldiers nearly anywhere they go, it should be usable in all terrains. This means it should be able to go into road and field, and even highly difficult terrain where a soldier usually dismounts or even must dismount.

It should be possible to operate the UGV from a distance, in case it is not with the soldiers at a certain moment in time. It must be possible to tell the UGV to wait at a certain location while soldiers move on,

and must come forward when called to bring goods. To be useful, the UGV must operate for at least 48 hours at a time, and preferably should weigh less than 100 kilograms. The UGV should also be usable to carry wounded soldiers.

For the users, the UGV should be able to provide power to the squad equipment like computers. The UGV should also provide a communication up-link.

The UGV should have self-defence against thieves, and should memorize who tampered with the UGV, for instance when it has been left parked for some time.

# Chapter 4 – TECHNOLOGICAL GAPS AND THE WAY TO CLOSE THEM

The six technological groups established their current status of technology, but they also identified the gaps they foresee for the year 2008 between the user requirements and the then expected technology status. For each of these technological groups, the most important gaps are described below. Details on the current status of technology are included in Annex C.

## 4.1 TECHNOLOGICAL READINESS LEVELS (TRLs)

To describe the current status of a technology, an internationally accepted standard was used: the so-called Technological Readiness Levels, or in short the TRLs.

The TRL is a number ranging from 1 to 9 expressing the maturity of a technology.

The lowest level, 1, means that just the basic principles of a technology have been observed and reported, so that technology is just in a very initial state.

The highest level, 9, means that the actual technology has been developed and even has been tested in actual missions where it proved to function properly. So at that highest level the technology is fully operationally usable.

A concise overview of the real-life meaning of the various TRL codes is given in Figure 4-1. More details on the TRLs and definitions of the various values are found in Annex A.

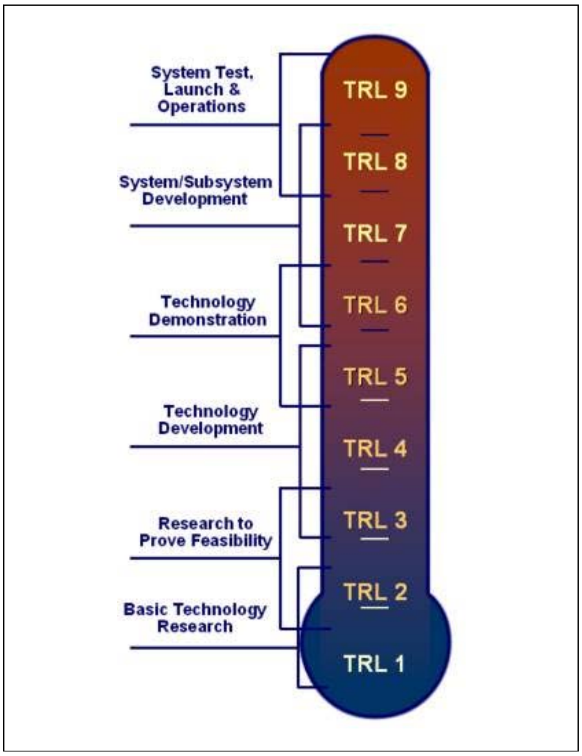


**Figure 4-1: Interpretation of Technological Readiness Levels (TRLs).**

## 4.2 2008 FEASIBILITY

To find an expected “gap” in technology under the current technology development speed in 2008, it is needed to express the confidence that the technology will reach the required level of readiness by the year 2008 under the current conditions.

The required level of readiness for 2008 was defined as TRL 7, meaning that **by 2008 a system prototype demonstration in an operational environment is considered as the desired achievement.** Note that it was not required to have robot fully tested and operational by 2008 (TRL 9), as this was considered too ambitious and therefore not realizable. A system prototype demonstration in an operational environment in 2008 however was considered to be a goal that should be both doable and of sufficient value for military users to start with.

To express the confidence that by 2008 this TRL level 7 can be achieved by 2008, the technology groups used the scale shown in the table below. So, to express that it is to a great extent likely that by 2008 a technology has reached TRL level 7, the technology groups give that technology 9 points for the 2008 feasibility. But if it is only to a small extent likely that the TRL level of 7 will be reached by 2008, then the 2008 feasibility is rewarded only 1 point.

| Points | Meaning |
|---|---|
| 9 | To a great extent |
| 3 | To some extent |
| 1 | To a small extent |
| 0 | Not applicable |

Based on the comparison of this 2008 feasibility on one hand and the military users importance of the same technology on the other hand, expected gaps in required technology can be (and have been) identified and ranked.

The found gaps and current status are described below, in one section per technological group.

## 4.3 COMMUNICATION

Communication is essential for the use of all types of robot systems. In most cases, especially when using multi-robot systems, there is a demand for wireless communication to achieve high flexibility. In single robot systems, the communication system is usually used to control the robot and to get information from the system sensors (vision, radar, etc.). For example, in a reconnaissance and surveillance scenario the task is to gather information about the area surrounding the robot system. Multi-robot systems combine the functionality of several single robot systems to achieve a higher efficiency and to cope with scenarios that are more complex. In the surveillance scenario example an object could be observed from different positions and with different sensors. Through the results of a sensor data fusion process, it would be possible to gain a more complete and higher fidelity situational awareness. Because of cooperating robot systems, there is a potentially high diversity of demands upon the communication systems.

In the next section the currently available technologies and their usability for robots will be discussed. Thereafter the vital and important issues identified by the user group and their feasibility for the 2008 outlook are discussed. The last section summarizes these results and tries to give an outline of what is needed for a generic communication system for single and multi-robot systems and what such a system might look like.

### 4.3.1 State of the Art

Before discussing the different issues, we summarize the most widely used communication systems with special regard to their usability for robots, either for control or for transfer of sensor information. It should be noted that the majority of robot-oriented communication systems are Internet Protocol (IP)-based and as such rely on the underlying technology to provide the necessary resources with regard to bandwidth, jitter and reliability.

**Table 4-1: Communication Systems and Their Attributes**

| | Satellite | HF | VHF/ UHF | GSM/ GPRS | WLAN | Laser | Infrared | Fibre optics |
|---|---|---|---|---|---|---|---|---|
| **Range** | Global | Global | 10-50km | 1-3km | <500m | LoS | 2m | ~2km |
| **Bandwidth** | 20k-10Mb | <12k | 10k-200k | 10k-50k | <54 Mb | < Gb | <16 Mb | < Gb |
| **Latency** | 1 - 3sec | <500msec | <200msec | <200msec | <10msec | N/A | N/A | N/A |

#### 4.3.1.1 Satellite

We differentiate the use of satellites in a robot environment because of specific unresolved issues. These issues involve transmitting on the move, especially in an urban environment, combined with a high latency dependent on the number of satellites in view the problem of navigating a robot which is not yet solved. It is however possible for a robot to transmit sensor and video data utilizing the available high bandwidth.

A possible scenario would be to use one satellite-equipped robot as the uplink for a group of robots or for fast distribution of sensor data while being operated (controlled) utilizing another communication technology. This uplink would have to be tightly focused to avoid ground-based detection, while the downlink itself would be detectable but the exact location of the participants would not be easy to pinpoint.

The size of the equipment could make such scenarios possible using at least medium-sized robots, while the problems with power consumption and the size of the satellite-dish would have to be solved.

#### 4.3.1.2 HF

High Frequency (HF)-based communication systems are comparable to satellites in most fields. The main differences are the low available bandwidth of today’s equipment together with an error-rate depending on the environment as well as on weather conditions. In addition, the equipment size, especially for the antenna, the power consumption (imagine the currently needed battery pack for a 400W amplifier) and the resulting necessary shielding of the other electronic components are limiting factors for the use in robots. Combining these facts a HF-based communicating robot is very susceptible to reconnaissance and subsequent jamming or attack.

On the other hand, HF can be used while on the move and does not rely on Line-of-Sight communication, and would therefore be applicable in an urban environment.

A possible scenario for a HF-robot would be as a decoy or as a remote backup system.

#### 4.3.1.3 VHF/UHF

The range of up to 50 km combined with the available bandwidth would make VHF/UHF-communication an almost ideal backup-system in a robot environment. The drawback is the latency of 200msec, which is

still too high for robot navigation. At the same time, the bandwidth is still too low for the transfer of live video sensor data to the operator at a rate higher than 10 frames per second (FPS) leaving no bandwidth for other information.

Other problems are similar to the use of HF equipment regarding the size, power consumption and the susceptibility to reconnaissance and jamming; these are as of now still unsolved.

#### 4.3.1.4 GSM/GPRS

The main weakness of GSM-based communication is its dependency on the base-station. The more recent developments in the area of Tetra and Tetrapol allow point-to-point communication without a base-station, but for group communication, this is not a viable solution. In today's urban environments there exist a number of base stations, which could be used, but with a number of problems. Firstly, these base-stations are usually under foreign control and will not be available for the exclusive use of one party. Secondly, the commercial stations depend on a civil power supply that cannot be guaranteed in every scenario. The alternative would be the use of portable base-stations, which then would have to be guarded against attacks, jamming or even theft. There have recently been experiments with the utilization of airborne relay-stations, which are even more vulnerable to attacks and jamming.

Robots could use GSM communication for control, low levels of sensory data as well as inter-robot communication.

#### 4.3.1.5 WLAN/Bluetooth

The use of WLAN, and even of Bluetooth, is a viable proposition for employment in robot systems, especially multi-robot systems. The comparatively short range, depending on the version of the IEEE 802.11 protocol used, is very useful in an open environment with regard to reconnaissance. Longer distances could be bridged by daisy-chaining robots or scattering autonomous relay stations, which could then also be used as a sensor network. Solutions to the problems related to daisy-chaining, like a higher latency and a higher error rate, will need to be researched.

High bandwidth and low latency allow the controller to operate the robot practically in real-time with a high degree of feedback from its onboard sensors without the necessity of Line-of-Sight. WLAN equipment can also readily be used in an urban environment due to its frequency management but with a reduced range and bandwidth. Robots can stay active for longer periods of time because of the smaller size and power consumption of the WLAN.

As with every other wireless technique, WLAN and Bluetooth are vulnerable to jamming and reconnaissance activities even though Bluetooth uses a Frequency Hopping Spread Spectrum (FHSS) mechanism.

#### 4.3.1.6 Laser

The advantage of lasers for communication is the high bandwidth coupled with a low probability of detection and the high robustness against ordinary broadband jamming methods. However, on a moving platform like a robot, apart from maintaining the laser link between an operator and the moving robot, there are further problems to be solved. For one, there is a high dependency on good weather conditions. In a foggy, dusty or otherwise cloudy environment, the laser beam will loose too much coherence to maintain the data link. In addition, a laser is strictly Line-of-Sight, which precludes most activities in an urban environment. The use of lasers in multi-robot communication has still to be addressed.

A possible scenario would be to combine a laser with satellite or HF equipment, use the robot as a remote relay station and transfer all communications using the laser to the local participants.

#### 4.3.1.7 Infrared

Infrared communication can be used for short-range activities where a Line-of-Sight connection is given at any time. The newer protocols like VFIR (Very-Fast-Infrared) support a bandwidth up to 16Mb/sec, enough for control and sensor data, while the range of up to 2 meters is deemed to low for most scenarios.

#### 4.3.1.8 Fibre Optic Cable

The use of cables is well established in the communication area as well as several military applications (e.g. TOW-guided missiles). Robots equipped with fibre optics could be used, for example, in hazardous environments with a high degree of radiation or where it is crucial that no communications can be intercepted. A possible scenario would be a bomb disposal robot, guided by the operator from a safe distance. With today’s fibre optic cables distances of well over 2km can be reached, while ensuring a very high bandwidth with a low latency.

Assignments in an urban terrain as well as in forests would be feasible, where each area includes its own set of problems. The use of multiple robots with fibre optic cables would pose a problem, as well as the vulnerability to accidentally or intentionally separated cables. A backup based on a wireless system would mitigate this weakness.

### 4.3.2 The Vital Gaps

#### 4.3.2.1 Intrusion Detection and Prevention

2004 TRL: 3
2008 Feasibility: 3

All aspects of communication security, especially authenticity, confidentiality and integrity, are considered essential for military environments. This also applies to communication with or between robot systems; as such communication may contain sensitive information like sensor data or the geographical location of military units.

A possible intruder of a robot communication system might not only be able to disturb the collection of sensor data or interrupt a video transfer, but also gain access to sensitive information or interfere with transferred data in other ways, maybe to forge sensor information or fake a video transmission (a “man-in-the-middle attack”). Where robots aggregate automatically into an ad-hoc network, an attacker could possibly implant an additional node into that network that tries to collect, suppress or manipulate transferred data or influences the logical connectivity of the other nodes, e.g. by routing manipulation.

On the one hand, it is obvious that communication channels need to be encrypted and communication partners (even robot systems) must identify themselves using cryptographic mechanisms. On the other hand, it would be useful to apply additional measures onto the network that allow detection of intrusion attempts and other suspicious incidents within the network domain.

For all scenarios considered here, the military relevance of intrusion detection and prevention is thought to be very high. When designing an intrusion detection/prevention system (IDS), however, the additional network load imposed must be taken into account for the design of the communication system in general (building an IDS infrastructure), especially when bandwidth constraints are an issue. Thus, the design of intrusion detection and prevention should be closely aligned with the design of the communication framework. Perhaps the communication techniques and protocols themselves should provide features that support intrusion detection and prevention. One possible way forward would be to examine the communication network for intrusion possibilities, then change the communication design to prevent

intrusion (e.g. using encryption) and also establish mechanisms to prevent physical intrusion into the communication systems on the robots.

There is already much research in academia and industry on network intrusion detection systems in general. There exist multiple IDS implementations for wired networks, and solutions for (centrally) managed wireless networks, like WLAN access points, are emerging, but there is a lack of practical solutions for independent wireless networks (e.g. mobile ad-hoc networks), especially robot and sensor networks. Thus, we need some kind of knowledge transfer between network and robot research. This could theoretically be done until 2006.

#### 4.3.2.2 Protection against Jamming

2004 TRL: 6
2008 Feasibility: 3

In military scenarios where the robot is a long distance from its operator or where we need direct interaction of the user with the robots (e.g. when the robot is actively steered by an operator), there exists a high demand on protection against jamming. As far as wired communication is concerned (e.g. with fibre optics), an attacker normally needs physical access to the wire, but can then easily interrupt communication. If we use a ground-based wireless network for communication, an attacker needs a little more expertise to jam transmissions, but can do so from a remote location. More advanced equipment and knowledge is probably needed to jam a Satcom link.

This task can in part be performed independently from other items, but the sensitivity to jamming depends on the physical layer used for communication. Commonly used techniques to counteract jamming include frequency hopping, multi-carrier techniques, and ultra-wide band transmission. These technologies are currently available for military radios, but they must be applied to (multi-)robot environments, i.e. we need to combine these techniques with the communication network used for the robot system. This task can be carried out by industry partners with experience in the development of military communication systems within a short time.

#### 4.3.2.3 Re-Configurability of the Communications Network

2004 TRL: 4-5
2008 Feasibility: 3

In every scenario considered, there is a need for the robot network to reconfigure automatically in response to changes in connectivity to the operator or any other node. The response may be to reconfigure the whole network or single communication links. Whatever the reaction is, the network reconfiguration should not be noticed by running applications. The reconfiguration must be successful even under fast-changing link conditions.

The re-configurability issue should be addressed in combination with the network auto-configuration issue. It must be present before the overlaying information network is running.

With the concept of Software-defined Radios, whose main objective is the complete re-configurability of devices, this item would be solved for single communication links. However, there is also a need to develop special routing/forwarding protocols to allow multi-hop communications that take the reconfiguration issue into account. A solution could be to improve existing Mobile Ad-hoc Networks (MANET) protocols.

This issue should be addressed by electronics R&D, mainly in the military communications industry on the one hand, and academic network research on the other.

#### 4.3.2.4 Auto-Configuration of a Network (within 10 minutes)

2004 TRL: 2
2008 Feasibility: 3

The fast auto-configuration of networks is a vital user demand in every scenario that might use multipoint communications. The auto-configuration issue covers several parts of the general reconfiguration issue. Apart from initialization of the network, auto-configuration may be regarded as reconfiguration at network creation time.

Due to the close connection to the reconfiguration issue, these problems should be addressed together. Auto-configuration must be present before the overlaying information network is running.

There is a need for developing routing/forwarding protocols that allow multi-hop communication under fast-changing link conditions. The auto-configuration should be even faster than 10 minutes for networks of reasonable size (e.g. less than 50 nodes). There already exist several implemented mechanisms for wired networks. There are already a small number of implemented mechanisms for wireless networks, but these will not be robust enough to use with mobile robot systems.

Academic research will still need some time to develop protocols that take the specific properties of wireless networks into account. The protocols must also consider the demands of robustness, speed, bandwidth and security.

#### 4.3.2.5 Multipoint Communication with a Higher Range and Bit Rate

2004 TRL: 3
2008 Feasibility: 3

Multipoint communication with a high range and bit rate is a user demand for scenarios that include surveillance, robot control and all types of data acquisition (video, high-resolution images). Multipoint communication should be made possible for ranges beyond 100 m and in some cases even some kilometres.

When using direct communication over one hop this issue might not be feasible until 2008. Ranges up to 100 m with high data rates or ranges up to 1 km at lower bit rates should be feasible. Preferably, this should be done using the same underlying communication technique. It should be possible to control the robot in a multipoint communication network using low-quality video at 10 FPS.

A possible solution might be routing/forwarding protocols using multi hop communication. This solution requires placing relay stations to extend the communication region. This can be either an advantage or a disadvantage: On the one hand, the relays must be placed but on the other hand the network is harder to detect and relay stations may be lost without complete loss of communication. An extension to stationary relays is the usage of mobile relays. If a robot system is used as a mobile relay, it can react to bad or lost links and can search for a better location.

The development of the underlying technology to achieve higher ranges with higher bit rates on direct communication should be done by the civil or military industry with the help of academic research. The development of multi hop solutions should be the focus of the academic research.

#### 4.3.2.6 Inter-Robot Communication for Robot Cooperation Based on Sensor Data

2004 TRL: 4
2008 Feasibility: 3

This feature is important to all scenarios where multiple robots are used: Robots for reconnaissance and surveillance will have to exchange map data, e.g. Robots on different checkpoints might want to exchange visual and sensor data about vehicles and people passing. Requirements include reliable, timely, and high bit rate transmission.

The problem of multipoint communication with higher range and bit rate is closely related to this issue. Both issues should be researched concurrently. The multipoint communication issue might improve solutions found for this issue, as discussed below.

A solution for inter robot communication is the development of mobile ad-hoc network protocols that take the special requirements of inter-robot communication into account. Since special mobile ad-hoc network protocols seem to be a solution for a generic robot communication system they are discussed in the summary section.

The development of a system for inter robot communication can be done either by civil or military industry with support of academic research. The level of academic research should be increased in this area.

#### 4.3.2.7 Communication in Unstructured and Urban Area

2004 TRL: 7
2008 Feasibility: 3

The ability to communicate in unstructured and urban area is apparently a vital demand for all five scenarios.

In principle, communication problems arising from the topology or structure of the operational area are closely related to the higher range problem listed above, as natural or human-made obstacles, like hills, mountains, forests or buildings and tunnels limit radio transmission and aggravate fading effects, especially at the higher frequency bands needed for high data rate transmissions.

Therefore, we see the same two approaches for this problem: either develop a new radio system that will work better in situations without line-of-sight and massive obstacles, or develop a method and protocols to use multiple radio devices (mobile or stationary) as relays, thus building a self-configuring communications infrastructure in the operational area.

Satellite links may be of advantage if line of sight can be maintained. This will not always be the case, especially if the robot(s) need to traverse unstructured areas (and hence undergo fast changes in orientation) or enter buildings (no line of sight at all). One solution could be a mixed setup with a stationary robot as a Satcom relay and radio links to the other robots. Other solutions might make use of multi-hop techniques with Wireless LAN based radios to build a chain or mesh of robots and other devices as relays.

Development of a new radio system (or adapting an existing system for use on robot platforms) would be a task for civil and military R&D, whilst the design of a self-configuring infrastructure might be of more interest to academic research.

### 4.3.3 The Important Gaps

As important though not vital, following gaps on communications were found.

#### 4.3.3.1 Working Communication in Radioactive Environment

2004 TRL: 2
2008 Feasibility: 3

The effect of nuclear radiation on a communications system is considered to be at least twofold: firstly, the electronic components of the communications hardware will be damaged. The strength of this effect depends on the type and intensity of the radiation and the exposure time. Secondly, an increased atmospheric ionization will probably lead to a damping effect on electromagnetic waves in the LF to UHF range and thus to quicker fading in radio links. The strength of this effect depends on the amount of ionization, i.e. on the radiation intensity. Thirdly, nuclear decay of isotopes will supposedly lead to an increase in background noise and lower the signal-to-noise ratio of radio transmissions. Details of these effects will need further investigation.

The robot platforms themselves should be able to withstand medium radioactive contamination, which includes a radiation-hardened communication system. This is closely related to the work of the Robot Platforms group in this workshop (e.g. shielding of vital components).

The possibility and level of radioactive contamination in the operational area must be considered for transmission range estimations – more intense radiation means a shorter transmission range and may lead to a loss of contact with a robot entering a highly contaminated area.

It is the responsibility of the military communications industry R&D to provide radiation-hardened electronics components, but fading effects caused by atmospheric ionization should be considered at the network design stage.

### 4.3.4 Summary

We have presented the collected issues, discussing the impact of each on future scenarios and application environments. Many of these issues have already been identified in related research areas, like the need for security in communication, protection against reconnaissance or the need for communication in urban environments. A very important issue is the necessity for multi-robot communication, which will have to be studied further, as well as other operational areas with their own subset of requirements.

The next generation of robots will communicate using an IP-based network, thereby being able to utilize many of the advantages but also importing a few new problems that are particular to the mainly wireless environment.

New robot communication systems should take the following requirements into account:

- Mobile and wireless ad-hoc communication;
- High ranges;
- High data rates;
- Multipoint communication;
- Adjustment to the varying availability of the network;
- Compliance with Quality of Service (QoS) demands;
- Prioritization of data;
- Secure communication; and
- Power awareness.

Many of these aspects have been researched for wired and wireless networks. For example, Quality of Service based protocols exist for wired networks, e.g. DiffServ, but for wireless networks the solutions are rare and for mobile ad-hoc networks there are no known appropriate solution. Some of these requirements (e.g. high ranges with high data ranges) can be met by improving the radio technology. But the problem is that current research treats these requirements as separate issues, while for an appropriate robot communication system they should be treated in an integrated manner in order to achieve a consistent and complete communication system.

A promising solution that may cover all of the requirements would be the development of special mobile ad-hoc network (MANET) protocols. Such protocols could be based on an existing solution but must extend such a solution to take all required aspects into account. As such protocols usually work as a routing protocol on the IP layer (part of the 7-layer OSI reference model) it could benefit from improvements in lower layers. Such improvements could be an improved radio technology or the support of different radios. Perhaps the integration of the Software Defined Radio (SDR) concept could be of advantage.

## 4.4 ROBOT PLATFORMS

This section first gives an overview of several currently available robot systems, and then gives a concise overview of the main user requirements concerning robot platforms.

### 4.4.1 State of the Art

As it soon became evident from the user requirements list as included in Annex B that no single UGV could fulfil all possible requirements, the state of the art on robot platforms is broken down by vehicle weight.

#### 4.4.1.1 Featherweight Robotic Vehicles

The user group identified the need for small easily deployable UGVs for use in an urban environment. Such battlefield robotic vehicles, commonly known as the featherweight size weigh in at under 5kg. These platforms are very easily transportable by a single person, exceptionally rugged and a few are light enough to be thrown by the user into the area of interest. Because of their low mass their operating time and capabilities are also reduced as such this scale of robotic devices is usually used for short term surveillance, local situation awareness and tactical information gathering.

These light weight robotic platforms exist today, they contain small, low power audio and video picture transmitters allowing troops the opportunity to throw one of these onto the roof of a building or drive it around a blind corner into an area of high risk before committing troops. The returning picture can show topography, target location, strength and state of readiness, etc.

Some of these featherweight UGVs can climb vertical steel structures, or traverse the upside down across the ceiling of steel structures such as containers, ships hulls, industrial buildings etc.

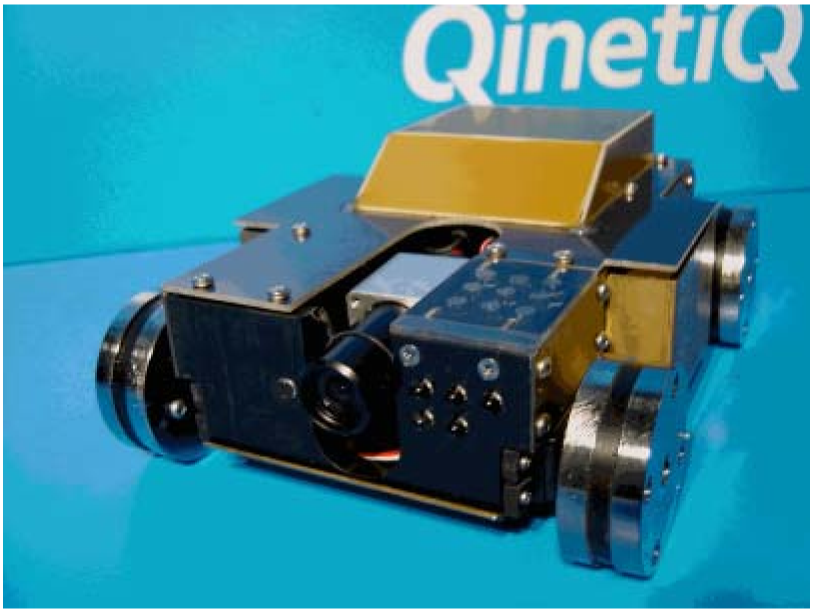


**Figure 4-2: QinetiQ "Magrat" Featherweight Information Gathering UGV – Fitted with Magnet Wheels.**

**Figure 4-3: Macroswiss "Crawler" Featherweight All Terrain UGV (under 20 cm length and 400 gr weight).**

#### 4.4.1.2 Man Portable UGVs

For this report it is taken that these UGVs weigh in between 5kg and 50kg. With their increased size and weight they also have increased capability in that they have an extended mission life, can cover a larger operational area and while the featherweight size of UGV is usually restricted to monitoring its surroundings this size of robotic platform can start to interact with its environment. Robots of this size are capable of supporting a low specification manipulator and are capable of carrying and deploying ordnance.

Such tactical robots have already been fielded by armies engaged in clean up operations where insurgents were entrenched in cave complexes.

**Figure 4-4: "Groundhog" Lightweight Inspection UGV Currently in Service with UK Forces.**


**Figure 4-5: US Army "PACKBOT".**


**Figure 4-6: Cybernetix "Castor" Man Portable UGV for Interventions in Hostile Environments.**

The limiting factor governing the use of these current man portable vehicles is the need for the operator to drive all of their functions, they have very little autonomy and can not make any command decisions. This means that they can not sense their environment and drive around obstructions or holes requiring the user to take all corrective actions during deployment. Early versions of battlefield robots had a reputation for system failures and missions were often aborted when the UGV failed. As more robots have been field tested their reliability has increased, however the scientific community believes that the user has an unrealistically high expectation on the capability of battlefield robots of this size, brought about mainly by their appearance in Hollywood movies. It should though be noted that while much of the capability portrayed by Hollywood is still fiction, much work is taking place to convert the hype into reality.

#### 4.4.1.3 Medium Weight UGVs: 50 kg – 500 kg

By numbers in use this grouping has by far the highest number of tactical robotic platforms currently in use by armies throughout the world.

The German army fielded "Goliath" an operational tethered remote control ordnance carrying platform in 1943. With the threat of car bombs in the Northern Ireland in 1970's the British army commissioned the design of the first dedicated IED disposal robotic platform and over the years this was developed into the family of "Wheelbarrow" EOD UGVs which are now in use throughout the world.

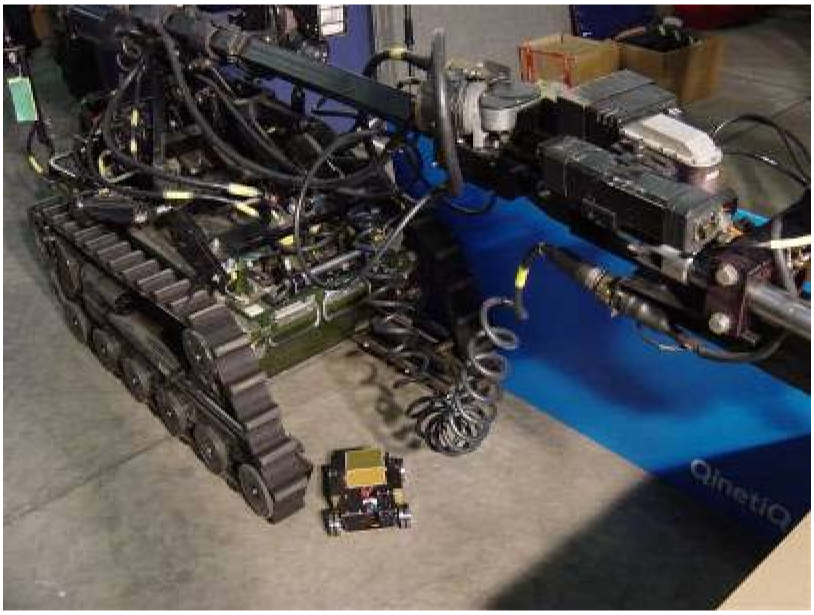


**Figure 4-7: "Wheelbarrow UGV" (with Magrat in foreground).**

As the threat has changed so too must the response. Military robotic vehicles designed to operate against traditional explosive IEDs or UXOs must now be capable of being configured to operate against new threats such as the release of radioactive materials (Dirty Bombs) and the use of chemical and biological devices by terrorists. This has spawned the next generation of these vehicles.

**Figure 4-8: Telerob "Teodor" Medium Weight UGV for Interventions in Hostile Environments.**

#### 4.4.1.4 Heavy Weight UGVs: Above 500 kg

This section contains most of the tele-operated battlefield engineering plant. The smaller vehicles include skid steer dumpsters like "Bobcats" and "JCB170's". These are based around commercially available building plant modified by the fitting of an "appliqué kit" to allow remote control from a safe distance. Larger civil engineering plant can also be converted for operation under remote control and radio controlled back hoe diggers and excavation machines have been converted by many defence industry contractors. Where such conversion takes place experience has shown that the need to allow the driver to be able to drive the vehicle as normal from the cab is a high priority.

**Figure 4-9: Cybernetix "AMX30B2" De-Mining Tank, Tele-Operated (French MoD via Giat Contract).**

Figure 4-10: JCB 4CX.

### 4.4.2 Essential User Requirements

Although a wide variety of user requirements to a robot platform are established, even to a great level of detail, many of them can be summarized into following list of features for a tactical robotic platform to be accepted into the battlefield environment:

1) Platform ruggedness, reliability and availability;
2) Modularity, a platform must be able to be configured to match its mission;
3) Its operational tempo must be compatible with the speed of battle;
4) It must operate in a real world environment where climatic conditions change as do topography and tactical protocols;
5) It should be intuitive to use, smart enough to avoid dangers but not undertake any unexpected or uncommanded operations;
6) It needs to be safe when working in close proximity to troops, public and wildlife;
7) Platforms must communicate to other resources, to share information;
8) It needs to be able to accept the current and next generation of sensor suites;
9) It needs to be EMC hard to withstand the electronic aggression associated with a modern battlefield;
10) It needs to be capable of decontamination post mission/conflict;
11) Support and training infrastructure to operate the vehicle systems must be kept to a minimum; and
12) It must be cost effective.

Some user requirements on robot platforms as found during the workshop are inconsistent in that they conflict with each other, at least given the current state of technology. For instance the required ability to negotiate great obstacles and to have a very long endurance, while at the same time the robot should be

very small. At least with current technologies the same of the robot and the obstacle are hard to combine, even more if a long endurance is required, usually meaning too great and heavy battery packs.

Essential for the reconnaissance scenario are stealth features, meaning low observability of the robot in visible light, infrared, radar and sound. The reconnaissance robot should be able to drive on all sorts of roads and terrains, negotiate slopes of up to 45 percent and barricades of several types of 0.5 meter and more in height. It should have only limited damage when being hit by an AT mine of 10 kg. It should have an endurance of several days without the need to refuel and should even be able to operate about 5 hours without the need to run the engines. In short, the UGV for reconnaissance has very high user requirements.

The other scenarios have less strict user requirements for the robot platform. But some have more demanding requirements, like carrying equipment that needs to move through very heavy terrain of up to 5 km/h and descend even steeper slopes in order to follow the soldiers. Also convoying has higher demands than reconnaissance concerning the range in kilometres and the speed in heavy terrain.

### 4.4.3 The Vital Gaps

Several user requirements lead to vital gaps on robot platform technology. These are described here, grouped by their common user aspect.

#### 4.4.3.1 High Speed Operation in Unstructured Terrain

Important for most of the scenarios is a relatively high speed in unstructured terrain. This of course is of relevance for reconnaissance, but also for tactical demining and carrying equipment for soldiers. Within this requirement, several technical gaps to close emerge:

- **Platform ruggedness**
  This is needed to ensure that the platform as a whole can cope with the great accelerations and decelerations in all directions that may be encountered in unstructured terrain.

- **Unit suspension systems**
  The suspension plays an important role in the forces passed on to the body of the robot. Active damping suspension systems may play an important role in this.

- **Drive trains**
  The latest very high efficiency motor drives and power train systems should be adopted to give very high mobility even when damaged. The drive trains must also be able to handle the great variations in short time frames in the required power and torque.

- **Configuration of the UGV (tracks, wheels etc.)**
  The current technology status prefers to select either wheels or tracks for specific types of terrain. For military operations however, it can not always be predicted which technique will be the best. During a mission a variety of circumstances may be encountered, each of which requires a different technique. Also aspects like sound production and endurance do not always match other user requirements.

- **Obstacle negotiation capabilities**
  Obstacles like heaps of debris of ditches are generally more easy to overcome when the platform is bigger. This does however not always match other user requirements.

- **Navigation and sensor capabilities plus computing power**
  Finding the best route in unstructured terrain under a variety of weather and light circumstances while driving at high speeds requires very fast and robust processing of great amounts of information from a diversity of sensors.

This gap can only be closed if more accurate information on the required robot size is available. Therefore the users should specify more clearly the size they need for robots for the various scenarios. Then industry and the R&D community can start engineering and testing possible solutions and systems.

To facility this approach, the user community should establish a working/speaking group to which the industry and R&D community can refer to obtain information on the needs (unclassified data). This interface group should be also made available to the other groups (i.e. sensors, multi-robot, etc). Potentially the EURON network could be used to host the web-based platform on which exchange information.

We envisage that this interface group should give industry and R&D community detailed information on the scenarios to be faced as well as give the users a possibility to share views and opinions and prepare face to face symposiums and meetings to further detail the needs. In a similar fashion the industry and R&D community should be part of this same organization in order to establish a cooperative network between industry, R&D and users.

On the technical side the following issues are crucial in order to obtain high speed operation on rough terrain:

- **Weight reduction of platforms (including all systems)**
  This is a design issue that should be taken care of mainly by industry if feasible systems are to be fielded in 2008.

- **Improvement of materials (composite materials, smart materials, self damping, etc.)**
  Industry needs to exploit the materials state of the art to its fullest by tapping into the current 2004 applied R&D knowledge base.

- **Improve suspension systems design (active damping, passive damping, etc.)**
  This is a design issue that should be taken care of mainly by industry by incorporating existing COTS technology into new UGV platform, if feasible systems are to be fielded in 2008.

- **Experiment with alternative locomotion methods**
  Industry should immediately undertake research on alternative locomotion methods, tapping from the existing R&D base, while the user community should provide industry with the necessary funding for this R&D since this kind of research is unlikely to be carried on independently by industry.

- **System ruggedness standards must be upgraded and research in impact resistance** must **be implemented for all systems**
  Design issue that should be taken care of mainly by industry (suppliers and integrators). If feasible, systems are to be fielded in 2008.

- **Sensing (real time sensing and remote sensing), navigation and processing (**including **mission planning) must be capable of handling the new challenges deriving from high speed operation**
  Sensor and navigational issue that ought to be taken care of by appropriate group.

#### 4.4.3.2 EMC Hardening

Although not specified as a requirement by the users, the robot platform group found that EMC hardening is a vital issue for all military scenarios. Failure to achieve this target would affect in a major way the functionality of the system.

Design of units must include EMC shielding from the beginning of the engineering process, in order to design such a system research must be undertaken to identify the levels of EMC that would be detrimental to the vehicle in battlefield conditions.

In order to close this gap the results of the research detailed in the previous point must be examined and taken into account in the design of the new UGV platforms. The user community should provide industry with the relevant (unclassified) information in order to implement the data in the design.

This gap is to be closed by industry and R&D community in close cooperation with the user who must provide information on the kind of military countermeasures the system is likely to face on the battlefield. Following the gathering of relevant information this becomes a design issue that should be taken care of mainly by industry if feasible systems are to be fielded in 2008.

#### 4.4.3.3 Repeated NBC Missions and Environmental Hardness

For proper military use, a robot should be easy to clean after return from an NBC mission in order to be able to use the robot again for a next mission.

Although the users did not request the functionality of easy NBC cleaning, and failure to achieve this target will not affect the functionality of the system, the robot platform group found that this actually is a vital issue. The reason is, that failing to achieve this target will reduce the range of missions of the proposed UGV as an NBC contamination that can not be removed will lead to a single-time use of the robot, which is too costly for most scenarios.

The capability of decontamination of the UGV from NBC agent is considered a highly desirable feature in all scenarios.

Design of units must include decontamination as well as environmental sealing aspects from the beginning of the engineering process. Industry should start designing UGV systems which are capable of being decontaminated.

#### 4.4.3.4 Enhanced Endurance

In order to achieve the user required endurance for some tasks, several measures are required. Most of these measures focus on power consumption and power storage. The proposed approaches to enhance UGV endurance are:

- **Power consumption reduction**
  This includes reducing the standard operational power consumption rate of all the electronics and sensors on board.

- **Power storage**
  More energy-dense power sources are required. This highly specialized topic however cannot be addressed by UGV R&D community, but only by the specific energy storage and generation R&D community.

- **Intelligent power management**
  Implementing intelligence on power consumption by (partially) downing components that are not required at a certain point of time is another approach to power consumption.

- **Improve mechanical efficiency**
  This means less mechanical energy losses and therefore less energy consumption. For instance improved drive trains or gearboxes.

- **Improve reliability to reduce breakdown frequency**
  A reduced breakdown frequency will also extend the average endurance of a robot.

In all the proposed scenarios a better energy management and lower consumption are of very high relevance. In some cases it is a necessity to accomplish the mission needs (i.e. reconnaissance, infantry carrier) while in other cases it is a useful bonus to the system. Failing to achieve this target will reduce the range of missions of the proposed UGV.

The problem of energy efficiency breaks down into two separate issues. The first issue is the evolution of current power sources and is outside the sphere of influence of the UGV research community and will, therefore, not be assessed in this roadmap. The second issue regards optimization of energy use and has to be addressed as a design constraint for the platform.

Industry and R&D community should integrate power-efficiency into the new UGV designs from the beginning of engineering for 2008. This effort is not limited to the platform development but must be considered by the other development groups as well. By 2008 we expect the problem to be improved but not entirely solved.

Strong emphasis is to be placed on reducing the electronics and computational systems to the absolute minimum necessary in order to save energy. Specifically computer OS should be considered in terms of power consumption and chosen with power consumption in mind.

Energy recovery systems must be evaluated at the platform level as well (regenerative braking and similar systems).

### 4.4.4 The Important Gaps

Several gaps on robot platforms were identified that are not vital for military operations, but still important. These important issues are discussed here.

#### 4.4.4.1 Limited Damage by AT Mine and RPG

The users required no mobility reducing damage due to Anti Tank (AT) mine of 10 kilogram and the capability of sustaining a hit from a Rocket Propelled Grenade (RPG). The robot platform group however has identified this point as being beyond feasibility on small systems by 2008 and will not be addressed.

#### 4.4.4.2 Very Steep Slopes

The users requested the possibility to ascend or descend a slope of more than 60% or drive parallel to a slope of more than 50%. This request, specifically in the aspect of not having an upper limit, is bound by laws of physics and not much can be done to deal with it.

#### 4.4.4.3 High Barriers

The users required the possibility to cross step shaped barrier of over 50 cm or to cross barricade of debris / rubble / stones of over 50 cm. This request is highly dependant on the size of the UGV and can range from very difficult (for very small units) to trivial (for big units). We believe that the step should be defined in terms of % of body height/length.

#### 4.4.4.4 High Speeds in Light Terrain

The users specified the possibility for some tasks to move forward in light terrain at speeds of above 70 km/h. While speeds above 70 km/h can be accomplished, the lack of an upper limit to this request makes it impossible to achieve this requirement as stated.

#### 4.4.4.5 Polar Climatic Circumstances

The users required the reconnaissance and equipment carrying robot to be usable under polar climatic circumstances. However, electronic systems in general and batteries in particular have severely degraded performances below –10°C and, as the user community has identified this as a highly unlikely environment, it has been decided not to address this in the roadmap.

#### 4.4.4.6 Payload Capabilities of More Than 100 kg

The payload is related to the scale of the UGV and should not be expressed only in absolute terms. We suggest to indicate desired payload capacities in terms of % of platform weight and size.

### 4.4.5 Summary

The science of operation of tactical robotic equipment in a real world environment is now mature enough to enable the military to field such equipment with confidence, provided the user defines his task and requirement in detail and has a realistic understanding of the capability of battlefield robotics. This means that at this time and date only for a limited number of relatively simple military tasks robot platforms may be used, especially those tasks that do not require a high level of robot autonomy.

By careful choice of the appropriate size of platform almost all requirements can be met but not in a single entity. As size reduces so does the capability and potential for extended operations, the limiting factor usually being the battery. As the platform size increases its potential to cause unintended injury or extensive collateral damage also increase but so does the system capability.

The prime reason to use robotic platforms is for missions or operations where human life can not be sustained or is at risk is beyond acceptable levels. As such they are ideal for operations inside contaminated areas, i.e. post explosion of a dirty bomb where they can be sent to measure radiation levels etc. They are ideal for long term behind the lines surveillance or guarding duties where the cost of keeping troops logistically supported is unwarranted and the featherweight size units are ideal for obtaining immediate real time tactical situational awareness.

While the science is mature enough to deploy robotic platforms today continued research and technical support will greatly enhance their capabilities in the future. Better sensors and algorithms will allow the vehicle to identify dangers and take the actions necessary to protect itself. Developments in battery technology will allow extend mission time, improved computation capabilities will allow full integration into ISTAR systems and advanced mission planning.

## 4.5 SENSING AND WORLD MODELLING

It is obvious that a single robot or a multi-robot-system will be the more mission effective and successful the more it is provided with situational awareness within its environment, supported by highly sophisticated sensor suits and world modelling capabilities.

The achieved level of situational awareness is strongly linked to its achieved level of autonomy. Autonomous behaviour is the result of software decisions without human interaction (for instance by means of agents), which decisions can only be made correctly on basis of a reliable and complete awareness of the environment.

Breaking down the desired requirements for a beneficial deployment of UGVs in the five most important military tasks, sensing and world modelling should facilitate at least following elements in autonomous behaviour:

1) Accurate information on the robot's own location and movements;
2) Accurate information on regions, locations, routes plus the ability for route planning;
3) Accurate information for obstacle avoidance ("sense and avoid") without a need for communication with other systems;
4) Automated detection and recognition of typical targets (ATR of operators, vehicles, traffic, buildings, animals etc.); and
5) Accurate information on the location and movement of other robots or other entities.

These technological aspects should be usable under all weather and environmental conditions and in all sorts of terrain. The information handling should be effective and efficient by using compression algorithms and by early filtering of information on relevance. Also, information handling should be done as much as possible on-board of the UGV in order to:

- Reduce the load on always limited available communication bandwidth;
- Reduce the possibility of being detected (however not relevant for all tasks); and
- Allow autonomous *come home* functionality in case of severe communication network problems.

Various techniques already exist for sensing on UGVs. Examples are infrared (imaging) sensors, (HD)TV/CCD-sensors, laser and acoustic sensors and even radar antennas or arrays, including mini-SAR (depending on size of robot). The choice for the sensor or sensors to use on a particular UGV is an important starting point for later decisions on hard- and software solutions within the overall robot(s) architecture for situational awareness. Unfortunately, sensors are just one of the most environmental conditions dependant technological functionalities. As an example within the infrared spectral band there are not only weather dependent range capabilities but also sight angle aspects and spectral bands to select from based on absorption and scattering effects: surface-surface vision with horizontal sight may then be best managed in the long-wave infrared (around 10 microns with 3 microns bandwidth).

### 4.5.1 State of the Art and Identified Gaps

Sensing and world modelling is strongly linked to scenario and system context. In particular the necessary sensor suite strongly depends on the robot payload capabilities as well as on environmental conditions and the main mission profile (e.g. transportation will differ from carrying equipment). During the workshop following five tasks have been analysed in more detail by the technical group and their gaps have been identified.

#### 4.5.1.1 Carry Equipment

Person tracking and following has been analysed as mature on flat surfaces and rural roads, and in some cases also in a kind of rocky terrain. But person tracking and following will give problems in for example forests and is not possible inside houses or other manmade constructions. Obstacle classification (for sense and avoid) is mature on flat terrain to a certain extent, but is not possible in forests and rocky terrain. Within world modelling the main problems occur when geometries of targets or obstacles are to be identified or terrain should be classified (surface conditions).

#### 4.5.1.2 Checking People and Vehicles

Sensing for navigation, short-range detection of explosives and recognition of people in vehicles were analysed as mature technology tasks. However, remote sensing of explosives is a future challenge.

#### 4.5.1.3 Transportation of Goods

Transport on roads, even within a kind of heavy traffic, and vehicle following on roads can be managed without problems. But mobility and missions in unstructured terrain and specific issues like identification of traffic signs are challenges for future technologies solutions.

#### 4.5.1.4 Mine Detection / De-Mining

This is identified as one of the most important issues for military and non-military users. A challenging task will be the detection of buried mines, which is identified even not applicable in 2008. Anti-tank mines will be more easy to detect than (various kinds) of anti-personnel mines and the same terrain problems as described with carrying equipment and transportation of goods occur!

#### 4.5.1.5 Tactical Information Support

Short range detection (less than 1 km) and incorporation in GIS is mature concerning persons and vehicles location and motion. Environmental mapping at the sensor's range is mature except for negative obstacles, like ditches and holes. Also available is nuclear and biological contact detection. The technological challenges arise within long range or non-contact detection tasks, the detection of negative obstacles and sensor-suites for co-operative situational awareness.

In relation to these identified top-ranked tasks the following section gives an overview of proposed technological roadmaps and identification of vital and important technological gaps.

### 4.5.2 Roadmap Scenarios and Requirements

The following technology gaps, in relation to sensing and world modelling, were identified as vital for attention. Sensing for UGVs can be separated in three main categories:

- Mobility function:
    - Obstacle avoidance and negotiation;
    - Terrain modelling and classification; and
    - Transport in normal traffic, including unstructured terrain.
- Payload function:
    - Mine detection, de-mining; and
    - Non-contact chemical and biological sensing.
- Combined mobility / payload function:
    - Environmental mapping;
    - Sensor fusion at limited visibility;
    - Situational awareness; and
    - Human and vehicle detection and recognition / identification.

Note that payload functions are mostly outside the robotics community, but they are very important and the integration and adaptation issues still remain as robotic issues! Also note that most of these issues are relevant for multiple military tasks.

### 4.5.3 The Vital Gaps

The following technology gaps, in relation to sensing and world modelling, were identified as vital for attention (the 2008 feasibility is scored on the 0-1-3-9 scale meaning *not relevant (0), to a small extent (1), to some extent (3)* and *to a great extent (9)*).

**Table 4-2: TRLs for Sensing and World Modelling Gaps**

| | Requirement | 2004 TRL | 2008 Feasibility |
|---|---|---|---|
| i. | Autonomous obstacle avoidance of negative obstacles (holes, ditches, cliffs) | 5 | 3 |
| ii. | Autonomous obstacle avoidance water pools in road of <1 m wide and <1 m long | 4 | 1 |
| iii. | Obstacle classification in urban terrain | 6 | 3 |
| iv. | Obstacle classification in rocky terrain and damaged urban area | 5 | 3 |
| v. | Obstacle classification in forests | 4 | 1 |
| vi. | Terrain classification (surface conditions) | 3 | 1 |
| vii. | Transport in normal traffic in unstructured terrain | 6 | 3 |

#### 4.5.3.1 Requirement i: Autonomous Obstacle Avoidance of Negative Obstacles (Holes, Ditches, Cliffs)

2004 TRL: 5
2008 Feasibility: 3

This requirement is essential for autonomous mobility as the vehicle's safety and survivability can not be guaranteed without detecting and avoiding holes, ditches, cliffs and other negative obstacles. By consequence, it is also essential for mission success. It is of great importance for the high mobility tasks, so for carrying equipment, transport of goods, de-mining and tactical information support.

It is expected that car industry will provide improvements to the technology base. This issue should be solved by 2008.

#### 4.5.3.2 Requirement ii: Autonomous Obstacle Avoidance Water Pools in Road of <1 m Wide and <1 m Long

2004 TRL: 4
2008 Feasibility: 1

This requirement is comparable to the avoidance of negative obstacles (holes, ditches, cliffs) and is related to the same four high mobility tasks. A difference is the surface that is present in case of a water pool, but yet can not be used for navigation. Also light reflection in pools under various environmental conditions is a complicating factor. Like negative obstacles, this requirement is essential for the vehicle's

safety and survivability as well as for mission success, and car industry is expected to provide improvements on this subject. This issue should also be solved by 2008.

#### 4.5.3.3 Requirement iii: Obstacle Classification in Urban Terrain

2004 TRL: 6
2008 Feasibility: 3

Classification of objects is part of the UGV's avoidance and negotiation logic, and therefore essential for vehicle autonomy. Without the right classification the vehicle may run into obstacles that frustrate the vehicle's mission, or the vehicle may try to find its way around supposed obstacles which in fact are not obstacles at all. Although it may not appear to be serious, this latter aspect may actually block the vehicle's motions while there is no reason, thus frustrating the vehicle's mission. This requirement is related to the high mobility tasks, so for carrying equipment, transport of goods, de-mining and tactical information support.

Especially in urban terrain, the safety of personnel in the vicinity of the vehicle is at stake when discussing obstacle classification. There should be good guarantees that people do not get hit by an UGV. A drawback of this guarantee is that it makes it possible for enemies to block an UGV by just standing in its way.

This requirement should be addressed before any other mobility issue, as it is essential for effectiveness and acceptance of UGV operations.

The R&D community involved in information science should put more effort in obstacle detection. A main issue in this is the variability of the obstacles that should be handled. Directions for research are the use of multiple sensors and sensor fusion. Car industry is expected to improve the technology base. Military will have to provide funds and clearer guidelines for terrains to be expected and for the desired functionality of obstacle avoidance.

#### 4.5.3.4 Requirement iv: Obstacle Classification in Rocky Terrain and Damaged Urban Area

2004 TRL: 4
2008 Feasibility: 1

This requirement is comparable to requirement iii, except that this one puts more focus on the vehicle's own safety and survivability while requirement iii puts relatively more focus on safety of persons in the vehicle's vicinity.

#### 4.5.3.5 Requirement v: Obstacle Classification in Forests

2004 TRL: 4
2008 Feasibility: 1

This requirement is comparable to requirement iii, except that this one puts more even more focus on the vehicle's own safety and survivability.

#### 4.5.3.6 Requirement vi: Terrain Classification (Surface Conditions)

2004 TRL: 3
2008 Feasibility: 1

Like obstacle avoidance, proper terrain classification is an essential precondition for vehicle survivability and therefore for mission success. A difference with obstacle avoidance is, that terrain classification is used both for strategic and tactical navigation – so it is more closely related to mission planning than obstacle avoidance which is almost purely used at real-time during actual driving. Good (usage of) information on terrain classification is significant for mission speed optimization and navigation. The terrain classification is part of the situational awareness.

By 2008 only partial terrain classification will be possible, being information on the geometry but less on the surface conditions.

Much R&D by the research community involved in information science is required. They should add to the environmental conditions that can be handled, including knowledge on long term and short term variations over time, i.e. seasonal changes. Research should focus on the usage of multiple sensors, sensor fusion, environmental sensors and texture analysis. Car industry will again provide some part of the technology base, and military will have to provide funds and clearer guidelines for terrains to be expected as well as for the desired functionality of autonomous mobility. The military should provide their current terrain models, forest terrain models and the NATO terrain mobility model.

#### 4.5.3.7 Requirement vii: Transport in Normal Traffic in Unstructured Terrain

2004 TRL: 6
2008 Feasibility: 3

This requirement is not only of importance for logistics, but also for autonomous mobility in general. In this report, "normal traffic" is seen as a mix of civilian and military transport. Although autonomous transport in normal traffic on roads is considered to be solved from a technological point of view around 2008, still legal issues will determine the military usability and unstructured terrain is a complicating factor. Besides, it is expected that complex terrain will be avoided anyway by the military when planning a transport. This reduces the expected required complexity of the terrain. This requirement is of relevance for carrying equipment, transport of goods and tactical information support.

This gap should be closed by a transfer of knowledge from the civil sector and by expanding or adopting this knowledge for military transport use. The main issue are the unstructured terrain as well as tracks that resemble dirt roads but at intermittent intervals. Research should also focus on the 3D relation between vehicles in a convoy instead of simple following (2D) on a road.

Closing the gap should be done by the research community involved in information science and sensor technology. The industry involved in transport, agriculture and forestry (car / truck manufacturers) will improve the technology base. The military will have to provide funds and clearer guidelines on the terrain to be expected as well as on the required functionality of autonomous transport. Government should address the legal issues of mixing manned and unmanned transport vehicles, the outcome of which might affect the required solution.

### 4.5.4 The Important Gaps

The following gaps were identified as important but not vital.

**Table 4-3: TRLs for Important but not *Vital* Gaps**

| | Requirement | 2004 TRL | 2008 Feasibility |
|---|---|---|---|
| viii. | Environment mapping at sensor range in buildings (including damage state) | 7 | 3 |
| ix. | Environment mapping at sensor range of negative obstacles on a route | 1 | 1 |
| x. | Sensor fusion at limited visibility | – | – |
| xi. | Situational awareness | 1 - 6 | 1 or 3 |
| xii. | Human and vehicle detection and identification | – | – |
| xiii. | Chance of not detecting a present AP mine < 1% | 2 | 1 |
| xiv. | Chance of not detecting a present AP mine 1..5% | 2 | 1 |
| xv. | Chance of not detecting a present AP mine 5..10% | 3 | 1 |
| xvi. | Chance of falsely detecting a non-present AT-mine <1% | 3 | 1 |
| xvii. | Detect chemical contamination at standoff distance of 1 km | 5 | 3 |
| xviii. | Detect biological contamination at contact | 6 | 3 |
| xix. | Detect biological contamination at standoff distance of 1 km | 3 | 1 |

This section now describes each of these requirements in more detail.

#### 4.5.4.1 Requirement viii: Environment Mapping at Sensor Range in Buildings (including Damage State)

2004 TRL: 7
2008 Feasibility: 3

This requirement focuses on mapmaking and ensuring coverage of the terrain. It is especially of importance for the reconnaissance task, by providing information to other troops or vehicles, but it also has its value for autonomous mobility in general. Because of this possible providing information to other vehicles, it is an ability that should be integrated in a military multi-robot system for reconnaissance.

The main issue is a damaged urban environment during a conflict, and especially 3D mapping. Mapping in 2D is considered solved. The solution should focus on hybrid mapping of semantic information (place recognition) and metric information. Mapping of completely unstructured terrain is more difficult and will not be feasible in the time frame up to 2008.

This gap should be closed by 2008 by the research community involved in information science along with a large portion of civil research. As a basis, industry must define relevant standards for information exchange while military must agree with industry on these standards in order to merge with present military databases. Military will also have to provide funds and clearer guidelines for the relevant environments as well as on the required functionality of mapping.

#### 4.5.4.2 Requirement ix: Environment Mapping at Sensor Range of Negative Obstacles on a Route

2004 TRL: 1
2008 Feasibility: 1

From a technical point of view, it is virtually impossible to map negative obstacles (ditches, cliffs and so) from a longer range. Therefore this aspect is believed to be unsolvable in the near future. It is of great importance of most high mobility tasks: carrying equipment, transport of goods and tactical information support.

#### 4.5.4.3 Requirement x: Sensor Fusion at Limited Visibility

2004 TRL: -
2008 Feasibility: -

This requirement was not scored explicitly during the workshop as it was not identified until quite late. Yet it was considered of importance for the high mobility tasks in order to enhance the value of gathered information, and to enhance the reliability and robustness for adverse conditions. Apart from adverse conditions, proper sensor fusion will also be useful for autonomous mobility in general.

This gap should be closed by 2008, by identifying complementary sensors, developing fusion algorithms and characterizing sensors for different environmental conditions. Also suitable representations for fused data should be identified as well as everything that is needed for specific task-environment combinations, like obstacle mapping for UGV obstacle avoidance. This should be done by the R&D community involved in information science and sensor technology. A large portion of this will be done in civil research. Military will have to provide funds and clearer guidelines for terrains to be expected and for the required functionality of ISR.

#### 4.5.4.4 Requirement xi: Situational Awareness

2004 TRL: 1 – 6
2008 Feasibility: 1 or 3

As “situational awareness” is rather broad, the 2004 TRL and 2008 feasibility vary depending on the information required for situational awareness. This requirement is especially relevant for the reconnaissance task, but also in general for any form of autonomous mobility or other tasks where the vehicle has to adapt quickly and autonomously to changes in its environment. This not only includes changes in terrain, but also in weather and threat conditions.

This gap should be closed by the R&D community involved in information science and sensor technology. A large portion will be done in civil research, for instance in car industry. Military will have to provide funding as well as clearer guidelines on the terrains to be expected and the required functionality of Intelligence gathering, Surveillance and Recognition (ISR). Research should be integrated with navigation and mission planning. It will also have to be integrated with multi-robot systems research, although to a lesser degree.

#### 4.5.4.5 Requirement xii: Human and Vehicle Detection and Identification

2004 TRL: -
2008 Feasibility: -

This requirement is relevant for reconnaissance, surveillance and ISR. The 2004 TRL and 2008 feasibility were not established as this requirement was found only at the end of the workshop. Nevertheless the R&D sensor and ATR research community should put effort in this, especially in adverse conditions. More research on identification a recognition is needed. The military will have to provide funds and guidelines for the terrains to be expected as well as the required functionality of ISR.

By 2008 some results are expected, but research will have to continue after that point.

#### 4.5.4.6 Requirement xiii: Chance of Not Detecting a Present AP Mine < 1%

2004 TRL: 2
2008 Feasibility: 1

This strict requirement is hard to tackle but essential for de-mining. It also is of some importance for carrying equipment, transport of goods and tactical information support. A major problem are buried mines and specific non-metal types of AP mines. The research community involved in sensors should work on this, and some results are expected in 2008. Nevertheless, research will have to continue after that for acceptable results in the long term.

#### 4.5.4.7 Requirement xiv: Chance of Not Detecting a Present AP Mine 1.5%

2004 TRL: 2
2008 Feasibility: 1

This requirement is totally comparable to requirement xiii.

#### 4.5.4.8 Requirement xv: Chance of Not Detecting a Present AP Mine 5.10%

2004 TRL: 3
2008 Feasibility: 1

This requirement is almost completely comparable to requirement xiii.

#### 4.5.4.9 Requirement xvi: Chance of Falsely Detecting a Non-Present AT Mine <1%

2004 TRL: 3
2008 Feasibility: 1

This requirement is almost completely comparable to requirement xiii.

#### 4.5.4.10 Requirement xvii: Detect Chemical Contamination at Standoff Distance of 1 km

2004 TRL: 5
2008 Feasibility: 3

Chemical detection at 1 km standoff distance is mainly of importance for tactical information support. Research has to be performed by the research community involved in sensor technology and chemistry. Some results will be available by 2008, but after that still more research will be needed.

#### 4.5.4.11 Requirement xviii: Detect Biological Contamination at Contact

2004 TRL: 6
2008 Feasibility: 3

Biological detection at contact is of importance both for tactical information support and for checking people and vehicles at checkpoints. Research has to be performed by the research community involved in sensor technology, chemistry and biology. Some results will be available by 2008, but after that still more research will be needed.

#### 4.5.4.12 Requirement xix: Detect Biological Contamination at 1 km Standoff Distance

2004 TRL: 3
2008 Feasibility: 1

Biological detection at 1 km standoff distance is virtually impossible considering current technologies, but will be of importance for tactical information support. Research has to be performed by the research community involved in sensor technology, chemistry and biology. Some basic results will be available by 2008, but after that still more research will be needed.

## 4.6 NAVIGATION AND MISSION PLANNING

Navigation and mission planning is essential to achieve an autonomous UGV, which in turn is needed to:

- Keep the operator out of danger;
- Minimise personnel requirements and costs;
- Simplify the driving task and extension of operator capabilities;
- Exploit roads as the fastest and safest route of deployment; and
- Allow interaction between manned and unmanned vehicles – which is vital.

This section includes three different aspects of navigation and mission planning that should be distinguished. Started from the top level we have the Mission Planning, the Path planning and the Navigation.

### 4.6.1 Mission Planning

Mission Planning (MP) as its name indicates is mission specific and considerably changes according to the scenario. Moving in convoys does not require the same planning as co-ordinating robots for enemy troop surveillance. Software for Mission Planning should contain intelligent algorithms that should ease the work of the planning officer. Timing constraints, resource constraints, tactical situation, NBC environment, payload, etc. are parameters that determine task identification & decomposition.

#### 4.6.1.1 Path Planning

Starting with the data provided by the MP, the Path Planning (PP) produces paths and waypoints taking into accounts the kinematics and dynamic capabilities of the robots involved in the mission. Path planning must rely on a Geographical Information System (GIS) in order to use realistic and reliable information. Results need be transferred to the robots for execution in case PP is not executed on-board the robots themselves.

Once the robot has received its instructions it will begin to follow the pre-computed path but as it is impossible to have a full model of the world with every single detail in the GIS, the robot will have to cope with obstacles along the way.

#### 4.6.1.2 Navigation

Navigation consists in avoiding those obstacles while following the initial paths. In order to avoid or pass obstacles the robots must be equipped with distance sensors (like ultrasonic, laser, radar or stereovision)

that will be used to build local maps. Local position sensors (inclinometers, inertial platforms) and odometry sensors (encoders) are required to build such maps and to fuse sensors' data. One sensor is certainly not sufficient for robust navigation and sensor data fusion is required for building terrain maps in order to avoid obstacles and to determine the traversability of suspect area.

In order to be able to recover from small path changes (obstacles avoidance and passing) a robot must be equipped with global position sensors (like Compass or (D)GPS). They are also necessary to allow operators monitoring their position and to co-ordinate their motion.

Control architectures for Navigation are generally deliberative, meaning that there is a strong coupling between the sensors data and the motion commands sent to the robot actuators. These architectures are based on simple behaviours that are combined using Behaviour Co-ordination Mechanisms (BCM).

If behaviours are viewed as operands, then BCMs are the operators used to combine behaviours into higher-level behaviours. BCMs can be divided into two main classes: arbitration and command fusion, which are complementary.

Arbitration mechanisms select one behaviour, from a group of competing ones, and give it ultimate control of the system (the robot) until the next selection cycle. This approach is suitable for arbitrating between the set of active behaviours in accord with the system's changing objectives and requirements under varying conditions. It can focus the use of scarce system resources (sensory, computational, etc.) on tasks that are considered to be relevant. Two possible implementations are:

- Priority-based arbitration: which is a subsumptive-style, where behaviours with higher priorities are allowed to suppress the output of behaviours with lower priorities.
- State-based arbitration: which is based on the Discrete Event Systems (DES) formalism, and is suitable for behaviour sequencing.

Command fusion mechanisms combine recommendations from multiple behaviours to form a control action that represents their consensus. Thus, this approach provides for a coordination scheme that allows all behaviours to simultaneously contribute to the control of the system in a cooperative rather than a competitive manner, which makes them suitable for tightly coupled tasks that require spatio-temporal coordination of activities. Examples of complementary mechanisms for fusion:

- Voting techniques (like Action selection architecture);
- Fuzzy command fusion mechanisms; and
- Multiple objective behaviour fusion (like Schema's based architecture).

When several systems are working together, it is necessary to manage a given number of supplementary tasks that are not directly productive but serve to improve the way in which those activities are carried out. The coordination of actions is one of the main methods of ensuring cooperation between autonomous agents. Actions have to be co-ordinated for four main reasons:

1) The agents need information and results produced by other agents;
2) Resources are limited;
3) We want to optimise costs; and
4) We want to allow agents having separated but interdependent objectives to meet their objectives while profiting from this inter-dependence.

The problem of the co-ordination raises several questions:

- With what should actions be co-ordinated?

- What is the mutual dependence between actions (space and time)?
- What are the relationships between actions (negative, neutral, positive)?

We can distinguish four main forms of co-ordination of actions:

- Co-ordination by synchronization;
- Co-ordination by planning;
- Reactive co-ordination; and
- Co-ordination by regulation.

#### 4.6.1.3 Co-ordination by Synchronization

To synchronize several actions it is necessary to define the manner in which actions are time-related, in order to time them in the right order and carry them out just at the right moment. Synchronization constitutes the lowest level of the co-ordination of actions. Petri nets are generally used to describe and solve the problems of synchronization.

#### 4.6.1.4 Co-ordination by Planning

Planning actions in multi-agent universes can be broken down into three distinct stages: making plans, synchronizing/co-ordinating plans and executing plans. One or several agents can be involved in these operations and consequently, the three main classic modes of organisation in multi-agent planning are:

- Centralized planning for multiple agents;
- Centralized co-ordination for partial plans; and
- Distributed planning.

#### 4.6.1.5 Reactive Co-ordination

In contrast to the previous approaches, reactive co-ordination considers that it is often simpler to act directly, without planning what one wishes to do in advance. All information relating to their behaviour is located in the environment, and their reactions depend solely on the perception they may have of it. When the agents have dependent goals and the actions of some can improve those of others, the general principle consists of using the capacities of reactive agents to react to modifications of the environment. Almost all techniques come down to the following ones:

- Use of potential fields (or vector fields); and
- Use of marks to co-ordinate the action of several agents.

#### 4.6.1.6 Co-ordination by Regulation

The principle is to set rules of behaviour that aim to eliminate possible conflicts. This technique is inspired by all regulations used to define what is good behaviour to avoid conflicts as far as possible.

In order to implement co-ordination, the system must at least provide the following capabilities: sensor information distribution and distributed behaviour communication and co-ordination mechanisms (for example through standard Message Passing Protocols like JAUS).

#### 4.6.1.7 Multi-User Cooperation

It is clear that multi-robot systems (MRS) will not be fully autonomous and that humans will stay in the loop for a while. In this case it is not sufficient to consider co-ordinations of robot actions but also to take

into account the communication and the cooperation between users. This aspect has received relatively little attention in the research community.

### 4.6.2 State of the Art

Currently sensors and processing software are good enough to autonomously follow roads made of tarmac (at least for real-life demonstration purposes), but some problems arise on dirt roads and brick roads. This is mainly caused by irregularities of the road's surface pattern. It also is already possible for robots to drive autonomously amidst other road-users, provided the speed is low (about 5 km/h) and the road is not very crowded. Autonomous navigation in typical military outdoor situations is quite close to becoming practically usable for terrains like high grass, sparse bushes and high bushes.

In some cases the robot will find such a great obstruction of its planned route that it can not be negotiated by obstacle avoidance but instead requires re-planning of the route. Currently this re-planning can be done very well autonomously, provided an up-to-date database with available roads is available. Should this database not be available, then the operator nowadays must and can manually input a new route to the robot. Autonomous resolution without the availability of a database with available roads is currently on the way of becoming possible, though that status has not been achieved yet.

Specific military related navigation restrictions like navigation along a route with maximum cover or even with intelligent avoidance of hostile fire are still a long way off from practical use as this is still very complicated.

Specifically for convoying applications, currently it is very well possible for an UGV to follow a leader vehicle provided that on beforehand the type of leader vehicle is well known, and preferably that leader vehicle is man driven. Following an autonomous, well defined leader vehicle is also already quite well possible although this concept is still less proven. A more general approach that would allow the UGV to follow any type of leader vehicle instantly is still a too complicated task to achieve.

### 4.6.3 Roadmap Scenarios and Requirements

For each of the five selected scenarios, the members of the group have listed the key issues concerning the navigation and the planning and evaluated their feasibility at the 2008 horizon.

Scenario 1: Reconnaissance and Surveillance

- Multi-robot collaboration for navigation and mission planning (UAVs/UGVs) 3
- 2D and 3D Map Building and Updating 9 - 3
- Multiple Goal Path Planning 3

Scenario 2: De-mining

- Mine Clearance (Manipulation problem) 3 - 9
- Autonomous Exploration, Search Patterns 9
- Precise Navigation (Platform and sensor issues) 9

Scenario 3: Convoying – Transport of Goods

- Convoying (see requirements table) 3 - 9
- Managing Goods (Automatic Loading – Docking) 9

Scenario 4: Check for Explosives

- Search under vehicles 9
- Search inside of vehicles (Robot Arm, Tele-Operation) 0
- Search persons for explosives (robot in vicinity of person or non-robot solutions) 3

Scenario 5: Carry Equipment

Needs different operation and mission planning modes (environment specific):

- Autonomous close following (to an assigned soldier) 9
- Autonomous loose following 3
- Meeting at a rendezvous point 3
- Situation awareness 3

By analysing and comparing the key issues in the selected scenarios, the group has identified the following vital navigation capabilities for military robots:

- Autonomous road following;
- Autonomous driving in mixed traffic (max speed of 50 km/h);
- Moving in all terrains with tactical behaviour in (nearly) all weather conditions; and
- Following leader (manned or autonomous), any type of vehicle.

### 4.6.4 The Vital Gaps

The analysis of the requirements that are considered vital to close the gap between military requirements and technical possibilities are grouped in following key capabilities for military use as was found during the workshop from the military user requirements:

- Autonomous road following;
- Autonomous driving in mixed traffic (max speed of 50 km/h);
- Moving in all terrain with tactical behaviour in (nearly) all weather conditions; and
- Following leader (manned or autonomous), any type of vehicle.

The vital user requirements within each group are shown in the table below, including the current TRL and the expected feasibility in 2008 to have reached the level of a system prototype demonstration in an operational environment (TRL 7). The table also gives the military relevance of each of these vital requirements (by definition high) and the ways to solve gaps identified.

**Table 4-4: TRLs for Gaps in Navigation and Mission Planning**

| Technical Issues | TRL | Feasible in 2008 (9,3,1,0) | Military relevance (9,3,1,0) |
|---|---|---|---|
| **Autonomous road following** | 6 | 3 | 9 |
| Obstacle avoidance | 7 | 9 | 9 |
| Obstacle avoidance (dynamic obstacle) | 6 | 9 | 9 |
| Route re-planning | 6 | 9 | 9 |
| All routes / All weather | 5 | 3 | 9 |
| Agree on real target scenarios, specify desired system for evaluation<br>Good weather system can be realised with today's technology. Improvements to all weather vehicles incremental and not realistic until 2008. | | | |
| **Autonomous driving in mixed traffic (max speed of 50 km/h)** | 3 | 3 | 9 |
| Avoidance of dynamic obstacles | 6 | 9 | 9 |
| Real time issues | 5 | 9 | 9 |
| Exception handling (emergencies) | 3 | 3 | 9 |
| Agree on real target scenarios, specify desired system for evaluation<br>Progress is constrained by laws and jurisdiction, regulations. Needs change in law. Reliability and safety issues. Liability. Redundancy. Mentality change. Human-robot interaction to be considered. | | | |
| **Moving in all terrain with tactical behaviour in (nearly) all weather conditions** | 3 | 3 | 9 |
| Possibility to autonomously navigate along a route with maximum cover | 2 | 3 | 9 |
| Possibility to autonomously navigate along a route avoiding hostile fire | 2 | 3 | 9 |
| Self-localisation | 6 | 9 | 9 |
| Spatial cognition | 3 | 3 | 9 |
| Traversability | 6 | 3 | 9 |
| Agree on real target scenarios, specify desired system for evaluation<br>Good weather system cannot be realised with today's technology. Depends on level of tactical behaviour. Terrain dependent. Improvements to all weather vehicle incremental and not realistic until 2008. | | | |

| | | | |
|---|---|---|---|
| **Following leader (manned or autonomous), any type of vehicle** | 7 | 3 | 9 |
| Local intelligence for exception handling | 6 | 3 | 9 |
| Local autonomy for route re-planning | 6 | 9 | 9 |
| Tactical formation | 5 | 3 | 9 |
| Master-slave communication | 8 | 9 | 9 |
| Obstacle avoidance | 7 | 9 | 9 |
| Obstacle avoidance (dynamic obstacle) | 6 | 9 | 9 |
| Agree on real target scenarios, specify desired system for evaluation<br>Some commercial systems available with manned leader vehicle (specific type).<br>Progress is constrained by laws and jurisdiction, regulations. Needs change in law. Reliability and safety issues. Liability. Redundancy. Mentality change. Human-robot interaction to be considered. | | | |

### 4.6.5 Summary

As an overall conclusion, vital gaps on navigation and mission planning were found for following key capabilities for military use:

- Autonomous road following;
- Autonomous driving in mixed traffic (max speed of 50 km/h);
- Moving in all terrain with tactical behaviour in (nearly) all weather conditions; and
- Following leader (manned or autonomous), any type of vehicle.

These gaps have to be closed by following actions:

- Concept and agree on real target scenarios, prioritise different driving conditions;
- Decide on and develop experimental systems;
- Organise trials (from lab to field prototype to fully operational);
- Define performance measures;
- Improve navigation technology through experimental systems;
- Manage a navigation technology group;
- Develop coordination and interaction with other technology groups; and
- Find funds.

In a graphical representation, most items on the way forward and their interrelation are shown in the figure below, while the time schedule for these actions for the four key capabilities is shown in Figure 4-12.

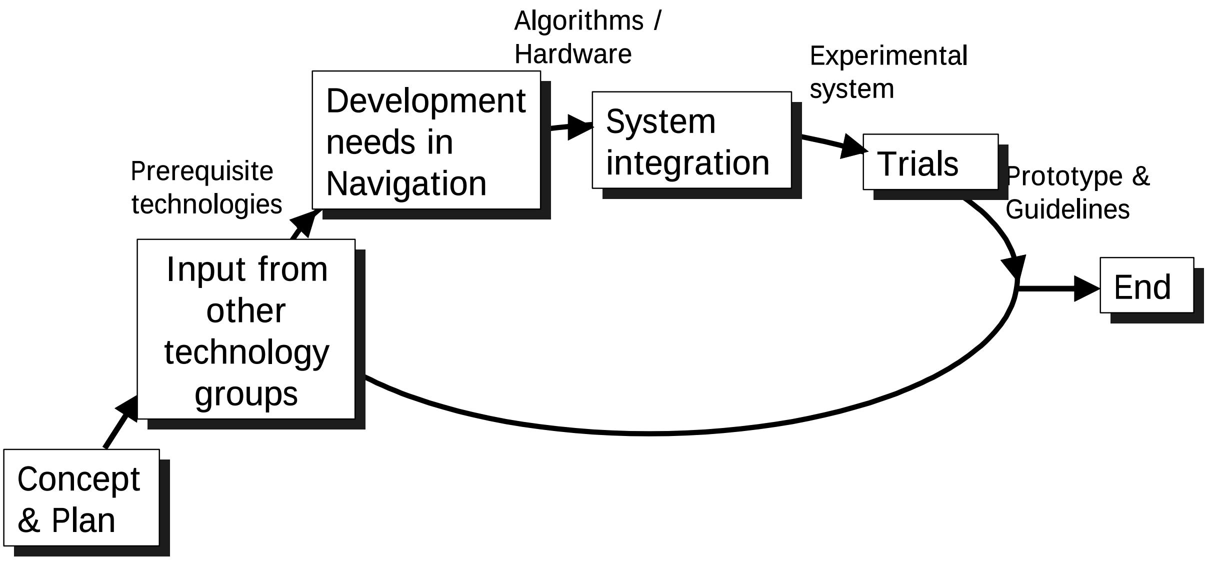


**Figure 4-11: Way Forward for Navigation and Mission Planning.**

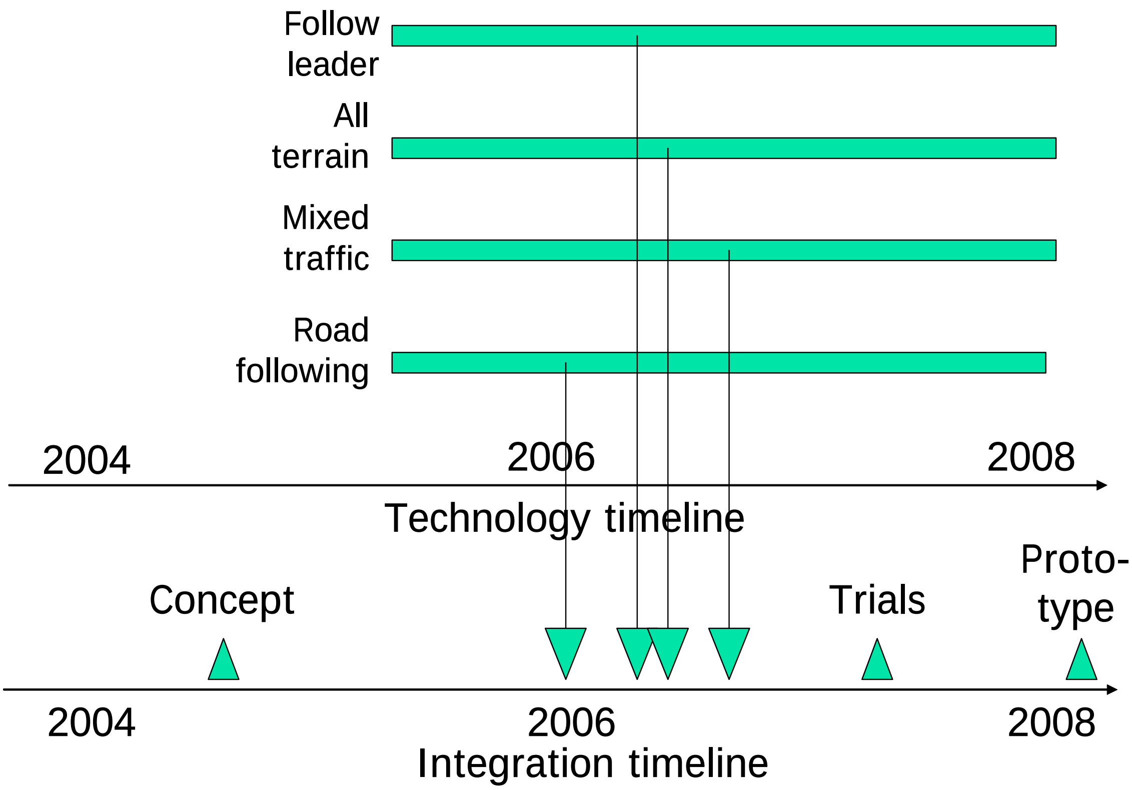


**Figure 4-12: Time Schedule for Navigation and Mission Planning Actions.**

## 4.7 HUMAN-ROBOT INTERACTION

While mastering the operation of a manually controlled UGV is a simple task, and operators can effectively be trained using existing equipment, the manual control was found to be insufficient for a realistic combat

environment and the more interesting discussion was oriented toward operation and training human operators of telerobots, which use a human supervised autonomous control method. The group found no problems related to the operation of manually controlled UGVs neither regarding the training of non-experts nor maintaining the capabilities of already well trained operators.

The difficulty on operating such unmanned equipment is related to the operator fatigue and awareness of combat activities at his site. For most combat operations (as well as in some other examples), in order to keep the soldier operator aware of the battle development and react quickly to improve his personal safety, it is mandatory to shorten the very long delay needed to the human operator to adapt himself from the remotely monitored environment back to the local real world. For remote operation in such environments, it is mandatory to upgrade from a continuous manually remote controlled system into a supervised autonomous one.

As a consequence of this discussion a new item was added to the list of technological issues, being evaluation of the feasibility of developing training of non-expert operators using Agent Based Systems. The discussion about training experienced as well as non experienced operators switched from manually controlled UGVs to the operation of expected supervised autonomous systems. Regarding the state of the art of the technology for training systems using "Agents", we found the technology at relatively preliminary state for enabling training of non-experts in very short periods of time (like 1 hour or even less than one week), as well as the feasibility to develop such equipment in less then three years (TRL=1). We are not aware of any activity aimed to develop such equipment. Nevertheless, if such an initiative will be taken the opinion was that the technology is well understood and similar systems are operational in other relevant areas. We assumed that training non-experts for operating relatively sophisticated equipment like the telerobots, would take one month and that operation is feasible to be done in the next years (TRL=3, 9).

We also found that the above mentioned discussion is similarly relevant to all the military scenarios considered during the workshop.

The "agent" terminology is quite new and so we assume less known to the community. By "agent" we mean a computer system capable of autonomous action in some environment. A general way in which the term agent is used is to denote a hardware or software-based computer system that enjoys the following properties:

- Autonomy: agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state;
- Social ability: agents interact with other agents (and possibly humans) via some kind of agent communication language;
- Reactivity: agents perceive their environment, (which may be the physical world, a user via a graphical user interface, or a collection of other agents), and respond in a timely fashion to changes that occur in it; and
- Pro-activeness: agents do not simply act in response to their environment; they are able to exhibit goal directed behaviour by taking the initiative.

Agents being autonomous, reactive and pro-active differ from objects, which encapsulate some state, and are more than expert systems as being issues which are situated in their environment and take action instead of just advising to do so. We need to build agents in order to carry out the tasks, without the need to tell the agents how to perform these tasks.

### 4.7.1 State of the Art for Essential User Requirements

Several user requirements on human robot interaction that play an important role in several scenarios were discussed in more detail in the technical group. Following is some background information on these issues.

#### 4.7.1.1 Workload/Occupation Level for Operator Performing Basic UGV Control in Simple/ Difficult Terrain

Remote task operations are slow and tedious due to difficulties of remote manipulation and viewing the controlled environment. Decades of experience within the remote operations community (i.e. nuclear), as well as recent combat experience in Bosnia, Afghanistan or Iraq show that remote tasks may take hundreds of times longer than hands-on work; even with state of the art force-reflecting manipulators and television viewing, remote task performance execution is five to ten times slower than equivalent direct contact work. Modest improvements in the work efficiency of remote systems can have high payoffs by reducing the job completion time. Additional benefits will occur from improved quality, enhanced safety and supervision of many platforms by the same human operator.

Under manual control the operator is in charge to close all control loops. In this mode of operation his workload and occupation is extremely high, nevertheless he/she misses valuable information needed to complete the task at the expected performance and quality. The technology needed to improve the information displayed is developed under the tele-presence and virtual reality technologies. We found that it is not feasible to reduce workload or occupation level under 25% of the current level. However, effort in this direction may reduce the workload under 50%, with some rise in the occupation level due to display of more information.

The group discussed the trends in technologies and agreed on the feasibility that the actions needed to reduce workload and occupation level for simple as well as complex terrains is to introduce a much improved control technique: Human Supervised Autonomous control.

Under supervisory control, an operator divides a problem into a sequence of tasks, which a system can achieve on its own. In multi-operator teleoperation, humans share or trade control. It is widely accepted that telerobots are the next coming technology, which will enable human intervention in order to improve the performance quality of operation of quite autonomous systems.

The group discussed the implementation of the supervised autonomous control of UGVs by introduction of controlling agents, which will be capable to represent the human operator in performing high bandwidth control activities and releasing the human to supervise and instruct the machine in performing more complex tasks. The evaluation of the availability of the technology needed is found out to be TRL=2, 3 in order to train the operator in two weeks up to one month. However, the feasibility to develop the technology and training equipment was evaluated as TRL=9 (one month), or TRL=3 (2 weeks).

#### 4.7.1.2 Possibility to Substitute/Support UGV Operator Training/Instructing using Interactive Simulations

For basic UGV control and manoeuvring we found the technology at system prototype demonstration stage (TRL=7) and the feasibility very high to implement during the next three years as TRL=9. Regarding the payload related control, the situation is much more complex, as depending on the payload itself and we evaluated the technology level at subsystem validation (TRL=5) and feasibility to implement during the short time as TRL=3.

#### 4.7.1.3 Possibility to Evaluate the Performance of the Human-Robot Team

This issue was found to be a difficult task, not really appreciated by users. Tech/TRL=4, Feasibility/ TRL=3.

#### 4.7.1.4 Possibility to Define Measures of Effectiveness for the Human-Robot Team

Fulfilling this requirement can be relatively easily achieved. Tech/TRL=5, Feasibility/TRL=9, but not required by the users.

#### 4.7.1.5 Possibility of Consistent Interface Design for Different UGVs for Common UGV Functions (On/Off, Manoeuvring, Parking. etc.)

Achieving this requirement beaks down into several smaller issues that should be addressed. These issues are:

- **Standardized controls (e.g. Manoeuvring)**
  This can be done but users required this capability only at the medium level of importance (TRL=3 for all scenarios). Tech/TRL=7, Feasibility/TRL=3.

- **Standardized symbolic representation (e.g. ISO, DIN, MIL based symbols)**
  This aspect is very important for all scenarios and required as 9, but the technology is not yet at the stage to standardize: Tech/TRL=2, Feasibility/TRL=1.

- **Standardized layout or sub-layouts for interface components**
  The users stated that this aspect is required as 9, even less achievable Tech/TRL=1, Feasibility/TRL=1.

#### 4.7.1.6 Possibility to Provide Robot Execution Plan to Operator Ahead of Manoeuvre

Having the execution plan ahead of manoeuvre is very important to the user (TRL=9) and less important as ahead of mission. Rom the technological point of view, it is easier to provide execution plans ahead of mission, but it is almost impossible to provide it ahead of a non pre-planned manoeuvre, one which is performed as response to a contingent event. Tech/TRL=4, Feasibility/TRL=3, 1. However, it is very feasible to provide plans after execution, or even in real time, when the meaning of “real time” is providing execution plans as done in parallel.

#### 4.7.1.7 Possibility to Scale Operator to Robot Ratio on Demand (Adapting to Unexpected Workload Peaks)

This aspect is of course a very important feature for the users, but we evaluated the technology as completely unavailable Tech/TRL=1, Feasibility/TRL=1.

#### 4.7.1.8 No Limitations on Interaction Caused by UGV Loosing Line of Sight (LoS) Contact with Operator

Continuous operations even in case of losing the LoS is seen by the users as an important feature (TRL=9). From the technical point of view, the meaning of this requirement is the need to improve the control method from a strict manual control to a teleoperated environment, which has no need to have line of sight between the operator and the robot. We also assume that users will even more appreciate a telerobotic environment, which release the operator to be aware of his local environment and perform multiple tasks.

#### 4.7.1.9 No Degradation of Performance (e.g. Speed, Accuracy) for Basic UGV Control when Operator is Wearing Protective Gloves/ Vest/ Full ABC Protection

This user requirement is practically existing.

### 4.7.2 The Vital Gaps

The following technical issues were found vital to solve:

- Workload/Occupation level less then 50% for operator performing basic UGV control in simple terrain / difficult terrain (75%);

- Possibility to provide robot execution plan to operator ahead of manoeuvre;
- Development of appropriate wearable user interface;
- Possibility to evaluate the performance and measures of effectiveness of the human-robot team;
- Possibility of consistent interface design for different UGVs for common UGV functions (standardized symbolic representation, standardized layout.). Possibility to scale operator to robot ratio on demand (adapting to unexpected workload peaks); and
- Non-degradation of performance because of use of any protective equipment (gloves, vest, NBC gear).

#### 4.7.2.1 Workload/Occupation Level

The current technological development is only conceptual, TRL=2 and we do not see this item to be feasible in 2008 (TRL=1), even that the military relevance for all scenarios is very high (all are 9).

1) For the checkpoint scenario it is important to lower the workload below 50% to improve awareness, reduce fatigue, probably enabling the supervision of multiple UGVs.
2) For the carrier robot scenario it is vital to lower the workload to reduce the interference on the soldiers more vital tasks. The interface development is vital to the task and should exist at the end of 2005.

The following issues relate to what should be done:

1) Teleoperation exists, but should be improved to provide better telepresence. Since this is a mature technology industry and military should cooperate in improving the cost performance ratio of telepresence. The major decision item relates to the expenses related to implementing and integrating more sensors and providing better understanding and feeling of the distant environment. The expected solution is task specific.
2) Automation of basic tasks (introduce control agents: use military codes, decide on parameters needed for control above servo-level). This issue has relevance to almost all aspects of involvement, starting with research to be yet done up to stabilizing standards.
3) Develop interface for upcoming autonomous behaviours/tasks, should as well be motivated by industry, while some aspects are still at research level.
4) Adapt robot interface to existing/planned command and control systems. This if a case of implementing mature technologies and as such should be initiated by military and done by industry.
5) Integration/merging of new subsystems into existing interface. This is a very general statement and as such should be treated by all participants: research, industry and military.
6) Make use of sensors introduced for autonomous tasks to improve also the telepresence. As supervised autonomous control evolve into a mature technology, sensors used for autonomous sensing may be helpful also to improve the manual mode of similar operations. It is common to assume that at test and evaluation stages of the telerobots, human supervisors should receive much more detailed information than needed for combat operation. This in order to enable real understanding of the robot’s autonomous operation. These instruments may also serve to improve the telepresence displays of similar systems.

#### 4.7.2.2 Possibility to Provide Robot Execution Plan to Operator

This item is more relevant to autonomous and semiautonomous UGVs, since in manual teleoperation mode the human operator follows a previously prepared plan or reacts to contingent events using his

experience and personal skills. The need for providing execution plan by the robot to the operator ahead of mission or ahead of manoeuvre is relevant today only for semiautonomous UGVs, since under current technology development conditions no one of the chosen scenarios is expected to performed autonomously. We evaluate the current TRL=4, but even the clear military relevance and need for all scenarios, in special its vitality for the reconnaissance and carrier scenarios, we assume that it is not feasible to develop it until 2008.

Provision of execution plans to the operator before the mission is possible for hybrid architecture based systems, but they can provide only plans for the expected events, while the execution plans for the contingent events, on which the success of the mission is very much dependent are done only a very short time ahead of manoeuvre. Presenting such plans for approval will cause the mission to fail. Research should provide methods later to be introduced into the development procedure. It should be continuously adapted during testing and evaluation as part of the project.

In order to close the gap researchers should consider trust in automation issues and develop improved task decomposition/modification interfaces.

#### 4.7.2.3 Development of Appropriate Wearable User Interface

Wearable interface components are beneficial for all scenarios by improving mobility and enable unconstrained tactical decisions, but it is vital to the carry equipment scenario.

Research should provide methods later to be introduced into the development procedure. It should be continuously adapted during testing and evaluation as part of the project. Research and industry should collaborate in developing new/better multimodal display devices (e.g. all time usable), new/better multimodal input devices, enable long operation times, while newly developed equipment should be lighter and more rugged.

#### 4.7.2.4 Possibility to Evaluate the Performance and Measures of Effectiveness

Measures of performance and effectiveness are crucial in order to support the introduction of UGV systems and enable their acceptance. This is important for all scenarios. Performance measures for UGVs are nowadays considered at conferences, like an annual workshop organized by NIST. This issue should be resolved prior to or alongside with system development.

However, evaluation of measures of effectiveness for the scenarios considered in this workshop will be done only if an initiative will be taken by participants of this workshop. Since these scenarios are quite common to many western militaries, some international interest may be reached to develop generally agreed measures of performance. Anyhow, collaborative teams including military and industry should work on detailed development of the scenarios to define the measures.

### 4.7.3 The Important Gaps

Following gaps were identified as important but not vital to solve.

#### 4.7.3.1 Possibility of Consistent Interface Design for Different UGVs for Common UGV Functions (Standardized Symbolic Representation, Standardized Layout)

Technology is not yet matured to enable agreement on industry standards, nor is it at the stage military standards may enforce their acceptance with relatively high performance and commercial success. However, standardized and consistent interface design is important to all scenarios.

This issue should be considered as soon as systems are becoming mature. Representatives of military, industry and researchers should be encouraged to initiate and participate in a working group on standard proposals. NATO should initiate a working group to consider laws and regulations using UGV in civil traffic. Industry and organizations like EURON, JAUS (standards organizations) should be referred to.

#### 4.7.3.2 Possibility to Scale Operator to Robot Ratio on Demand (Adapting to Unexpected Workload Peaks)

The current technology is not capable to adapt to unexpected workload peaks and rescheduling of tasks is still a very much open issue. Therefore it is not feasible to expect its implementation until 2008, even though the need and relevance is high for all scenarios considered. Of course, this issue is more important to scenarios having varying levels of workload during mission execution. The problem should be solved along with the development of the product. This may be done by developing distributed and scalable interfaces as well as developing control agents to take over some functions. The first two tasks may be attended by all, but the last one is still a research issue.

#### 4.7.3.3 Non-Degradation of Performance Because of Use of Any Protective Equipment (Gloves, Vest, NBC Gear)

The need is clearly stated, understood and even required by the military. For technology to respond to this requirement it is equivalent to reduction of the workload or the operator occupation level. In the situation where it is difficult, non convenient and even clumsy to perform remote operation it is even worse if the operator has to use for his personal safety any protecting equipment, or it may even make him feel unsafe in the combat environment. The solution to this problem will come along with the introduction of control agents and transfer to supervised autonomous mode of operation. Obviously, military should be considered during design of future protective equipment as well as design of future semiautonomous systems.

### 4.7.4 Summary

The following requirements were found vital or at least important to be listed on the NATO Road Map for (multi-) robot systems in military domains and be developed in the shortest possible term:

- Usability and performance of the human-robot team has a general relevance for all scenarios and is dependent on the underlying system.
- Workload reduction is required to improve the soldiers' awareness, reduce fatigue and impact on more vital tasks. The relevancy is higher for the checkpoint and carrier robot scenario.
- Development of wearable user interface to improve soldiers' mobility and enable unconstrained tactical decisions. It is relevant for all scenarios, but is dependent on development of wearable computers and wearable I/O devices.
- Measures of effectiveness for human-robot team by supporting the introduction of UGVs and their acceptance. It is relevant for all scenarios.
- Possibility to scale operator to robot ratio on demand by maintaining system performance at workload peak. It is relevant for scenarios having varying levels of workload.

## 4.8 MULTI-ROBOT SYSTEMS

This section describes the technology gaps identified by the workshop in relation to *multi-robot systems*. Firstly, we need to define what we mean by a multi-robot system here, as follows:

*A system, comprising more than one robot, in which the tasks and activities of the multi-robot system are shared between the robots. The nature of the task sharing could range from simple workload sharing, or*

*distributed sensing, to more complex co-operative or collaborative behaviours. The architecture of the multi-robot system could be fully distributed or it could have a hierarchical command and control structure. A special case are swarms consisting of large numbers of robots having simple behaviour rules and reacting on the actions of other robots in the swarm by local sensing only – so without explicit co-ordination or deliberation. Although simple in their individual behaviours, these swarms as a whole can emerge intelligent behaviour.*

It follows from the definition above that simply putting together a number of independently operating single robots does not comprise a multi-robot system. In order to meet our definition of a multi-robot system, there must be some element of work-sharing (including distributed sensing), collaboration, or co-operation between the robots so that they operate as a *team* rather than a collection of individuals.

In the US, DARPA has funded a great number of multi-robots systems research projects, located at several US labs, all aimed at fulfilling reconnaissance or surveillance scenarios. The majority of these DARPA projects use homogeneous robots, meaning a team of robots of the same design thus having equal capabilities. We can mention the most famous ones:

- **Cognitive Colonies**
  This project at CMU uses ActivMedia Pioneer II robots (*left picture*) for reconnaissance tasks, with an architecture based on information distribution.

- **Urban Search and Rescue**
  This project at South Florida University aims to develop a system for finding people in ruins. It consists of marsupial robots with the bigger helping the smaller to go beyond big obstacles whilst the small robot can observe into tiny holes. This project uses iRobot ATRv robots in combination with Urban Robot (*middle picture*).

- **An Intelligent Systems and Robotics Center (ISRC)**
  This project at Sandia labs that is based on the lunar exploration robot Ratler (*right picture*) has been developed also for surveillance tasks.

**Figure 4-13: Robots from US DARPA Funded Projects.**

In Europe, many projects like Martha (Multiple Autonomous Robots for Transport and Handling Applications, LAAS FR) tried to develop obstacle avoidance and anti collision between units, or co-ordination and adaptivity like Corom (Cooperation for Mobile Robots, LIRMM FR). Recently, the German firm Kuka developed a co-operative system in the automotive market with several robots collaborating for welding, moving, guiding and rotating pieces (*picture below left*).

Multi-robot systems are also a subject in the French MoD’s project BOA (Bulle Opérationnelle Aéroterrestre) that aims to demonstrate, amongst many other things, co-ordination capabilities between

UGVs and between UGVs and UAVs for a new battlespace (*artists impression below right*). A short term demonstration is planned in 2008, middle term coming in 2015.

**Figure 4-14: Co-operative Robotic Examples.**

It is important to note that, to the best of the authors' knowledge, these projects are still at an exploratory stage, meaning that there are no current operational examples of multi-robot systems in the strategic domain. Thus, unlike the other sections of this report, this section describes a **potential** rather than an **actual** technology. It is an exciting technology that could bring significant benefits, but there are also significant gaps between the current and the required technology readiness levels. Thus, significant work needs to be done before practical, operational multi-robot systems can become a reality.

### 4.8.1 Initial Assumptions for the Roadmap

In developing this roadmap for multi-robot systems the following initial assumptions were formulated during the workshop in close consultation with representatives of the users group. These relate in particular to the *level of autonomy,* which is a sine qua non for practicable multi-robot systems.

- The UGVs should be as autonomous as necessary (to relieve the operator from information and work overload), but…
    - Autonomous firing is not accepted by the military – they should always 'pull the trigger' themselves.
    - The operator must be able to override the autonomy of each single robot at any time for any reason, and take over control. This control must be possible at two levels: (1) specifying small tasks to the UGV like driving to a certain location and (2) taking over full control in tele-operating mode using a 'joystick' type of control.
- For certain tasks (like reconnaissance in hostile terrain) the amount of communication between the UGVs should be minimal to prevent detection and jamming / hostile parties taking over control.
- The UGVs by themselves are assumed to be capable of performing their tasks as single robots in a single-robot setting; this road map just focuses on the additional requirements to add multi-robot functionality.
- The UGVs should be able to self-organise.

*System integration*, in the sense of integrating multiple robots into a multi-robot system, is a key issue to deriving a functional multi-robot system. This must be borne in mind in considering each of the technology gaps identified in this report.

The starting point for multi-robot systems must be the overall systems architecture, so meaning the architecture that integrates the single robots into a co-operative superstructure. This architecture should be fed into other technical groups right from the start. Otherwise the single UGVs developed will not have the potential to be incorporated into multi-robot systems. Thus, co-operation with the efforts to develop the other robot system technologies should begin immediately and in such a way that the multi-robot systems provide an overall systems-level input to single robot design and specification efforts. This is an important recommendation of this report.

## 4.8.2 Scenarios Relevant for the Roadmap

Not all of the ‘five most relevant’ scenarios identified by the military users are considered appropriate for multi-robot systems. Thus, in developing the roadmap the multi-robot group focussed on the following three scenarios:

### 4.8.2.1 Reconnaissance and Surveillance for Tactical Support

A multi-robot approach to reconnaissance and surveillance has clear advantages over a single-robot approach. In particular:

1) Multiple robots operating as a team can be physically deployed and distributed across the terrain, thus providing greater simultaneous area coverage than could be achieved with a single robot;
2) Data from sensors on a number of robots can be fused in order to provide greater accuracy and confidence in estimating the disposition of objects of interest;
3) Robots in a multi-robot system can be smaller and simpler (perhaps with different robots with different specialist sensor types), thus these robots can be stealthier than the equivalent multi-sensor single robot platform; and
4) A multi-robot system can tolerate greater levels of failure or loss (of individual robots) while still providing overall system functionality (perhaps at a reduced level of fidelity).

### 4.8.2.2 De-Mining – Tactical and Post-Conflict

A multi-robot approach to de-mining clearly has the advantage that a large number of small, simple robots could potentially locate and mark mines across a larger area than could be achieved by a single robot in the same time. A team approach has further potential advantages. For instance:

1) The team could collectively map and hence discover the boundaries of a minefield more rapidly than a single robot; and
2) Robots with certain types of sensor (to detect the trace odour of unexploded ordinance, for instance) can share data to estimate the source of the odour plume to locate the mine.

### 4.8.2.3 Convoying, Transport of Goods

Convoying, by definition, implies a number of robot vehicles. Convoying using a multi-robot approach could, for instance, employ autonomous leader-follower algorithms such that the lead-vehicle navigates (or is tele-operated, or perhaps simply follows another vehicle with a human driver), while the follower-vehicles simply follow the vehicle in-front, maintaining a safe distance while matching its velocity.

## 4.8.3 The Vital Gaps

The following technology gaps, in relation to multi-robot systems, were identified as vital for attention.

**Table 4-5: TRLs for Vital Multi-Robot Gaps**

| | Requirement | Gap Rank | 2004 TRL |
|---|---|---|---|
| i | To interact with other robots performing different, specialised tasks | 1 | 2 |
| ii | To perform a task with multiple, collaborative robots | 2 | 4 |
| iii | To autonomously divide a task, specified by the operator, between several robots | 2 | 2 |
| iv | Co-operative Perception: to collectively recognise objects of interest | 5 | 2 |
| v | The ability to autonomously manage and prioritise events | 7 | 3 |
| vi | Co-operative Perception: the ability to share data from multiple sources | 7 | 5 |
| vii | To interact with other robots performing exactly the same task | 7 | 4 |

### 4.8.4 The Important Gaps

The following gaps were identified as important but not vital.

**Table 4-6: TRLs for Important Multi-Robot Gaps**

| | Requirement | Gap Rank | 2004 TRL |
|---|---|---|---|
| viii | Methodologies to validate and verify for functionality, reliability, and safety of multi-robot systems, during the development process | 4 | 1 |

### 4.8.5 The Long-Term Gaps

The following gaps were identified as of longer-term interest.

**Table 4-7: TRLs for Long-Term Multi-Robot Gaps**

| | Requirement | Gap Rank | 2004 TRL |
|---|---|---|---|
| ix | Methodologies to validate and verify for functionality, reliability, and safety of multi-robot systems, during operation | 9 | 1 |

Note that the requirements identified above fall naturally into a number of groups. Requirements i and vii are both concerned with interaction between the robots in a multi-robot system. Requirements iii and v are concerned with how tasks are divided and managed between multiple robots. Requirements iv and vi relate to co-operative perception, and tasks viii and ix are both concerned with the safety and reliability of multi-robot systems.

This chapter now describes each of the requirements in more detail.

#### 4.8.5.1 Requirement i: To Interact with Other UGVs Performing Different, Specialised Tasks

2004 TRL: 2
2008 Feasibility: 1

Any practical multi-robot system would require heterogeneous robots, i.e. different types of robot working together, as a team. This is important to military users since providing every robot with all of the functionality it might ever need for any role would be expensive and lead to over-large over-complex, and hence, less reliable UGVs. Instead military users prefer simpler single- or reduced-functionality UGVs, employing a modular approach (e.g. interchangeable sensors) for ease of procurement and maintenance. Each of these single- or reduced-function UGVs would need to be able to interact, inter-operate and communicate in order to act together as a team. Note that this requirement for heterogeneous robots appears to contradict the users combining (on the first workshop day) various surveillance or de-mining tasks into one robot, but actually it does not. The key factor is modularity, allowing the users to reuse the same platform as much as possible for various tasks with a minimum of effort, thus easing procurement, training and maintenance.

The work on this issue should start immediately and does not need to be completed earlier than 2008.

This requirement depends on reliable and secure communication with sufficient bandwidth (good compression and protocols). We require both peer-to-peer (meaning robot-to-robot) and robot-to-operator communication. For compact communications, we need good on-board sensor fusion and world mapping, but in some cases the robots will need to exchange larger data sets of sensor data to build a common world model.

A new program of research should be established on multi-robot interaction. This could be a European program, but a problem is that Framework 7 will not start until 2007, which is too late to meet this need.

Elements of this interaction are:

- Ad hoc communication;
- Co-operative perception;
- Formation control;
- Collective physical actuation; and
- Planning for teams of robots.

The research and industry communities should work together inside the program. In fact, they already do work together, but a lack of funding prevents desirable progress, therefore funding must be sought. A problem is that military users are interested in multi-robot systems but still have to consolidate funding. Another problem is that current multi-robot system research is ad hoc, as there is no real ‘user pull’.

A solution to this might be a European version of the US DARPA, being a private/public co-operation. This organisation should lobby for funding and define research demands. The initiative for such a private/ public co-operation should come from military users in the various countries, in mutual co-operation. This could be part of WEAG or OCCAR.

#### 4.8.5.2 Requirement ii: To Perform a Task with Multiple, Collaborative UGVs

2004 TRL: 4
2008 Feasibility: 1

For surveillance it is important to combine information on an object from different viewpoints, mostly from different sensors. The key issue is the increased reliability, fidelity (because of multiple viewing angles and sensors), coverage (surveying a greater area in shorter time and lower operator work and information load) and redundancy (when an UGV fails the other can take over tasks and reconfigure) when using multi-robot systems. Also a requirement is to automatically follow a suspected object when moving from the viewing range of one UGV to the viewing range of another UGV.

The interdependencies, time frame and recommended actions to be taken are identical to those described in requirement i “To interact with other UGVs performing different, specialised tasks” above.

#### 4.8.5.3 Requirement iii: To Autonomously Divide a Task, Specified by the Operator, between Several UGVs

2004 TRL: 2
2008 Feasibility: 1

This requirement is important for the operator as it reduces his workload very considerably (indeed, without autonomous task division, an operator may simply not be able to command and control a complex multi-robot system). In a system with autonomous task division the operator just specifies the overall task and its parameters and the UGVs divide that task among themselves, automatically.

This is technically demanding and we anticipate it can be solved only for specific scenarios and settings before 2008. We expect it to be soluble by 2008 for a less complex application such as convoying. Work should start right away.

This gap could be closed using the same approach as outlined for requirement i above, but also taking advantage of developments in task decomposition from multi-agent systems, multi-computer operating systems and industrial automation systems.

There are no specific interdependencies except from learning from the above-mentioned fields of interest.

#### 4.8.5.4 Requirement iv: Co-operative Perception: To Collectively Recognise Objects of Interest

2004 TRL: 2
2008 Feasibility: 1

For reconnaissance, surveillance and de-mining the fidelity of classification or identification is expected to improve when sensor data from various robots in the system are combined. For instance, looking at a potential hostile vehicle from different angles should give more precise information on the disposition of that vehicle.

By combining information from various robots, more complex tasks become possible.

We believe that for simple tasks in structured environment the collective perception task can be solved in 2006. More complex environments and tasks can be worked on from 2006 on.

Interdependencies exist with sensor data acquisition and processing, and also with communication (reliability and sufficient bandwidth). This task may benefit from distributed information processing techniques.

Approach as outlined for requirement i above.

#### 4.8.5.5 Requirement v: Ability to Autonomously Manage and to Prioritise Events

2004 TRL: 3
2008 Feasibility: 3

As already suggested (requirement iii) one goal is to reduce the information and workload for the operator, otherwise he may not be able to control the multi-robot system. In this way failures, such as robots executing undesired actions, are reduced.

This requirement differs from requirement iii in that here the UGVs have to react correctly during execution of their tasks, while requirement iii focuses on the initial task assignment when it is input by the operator at the beginning of the mission. If, for instance, we look into an MRS for surveillance tasks, then requirement v focuses on how to handle a situation where robot A has spotted a potential intruder and has asked other robots to assist in information gathering, while at that very moment another robot B from the same MRS signals another intruder at a more dangerous spot. Then the robots have to prioritize autonomously whether they focus on the event signalled by robot A or on the one signalled by robot B – or split their attention in a specific ratio between the two events.

For simple tasks (like de-mining and convoying) in structured environment this can be solved in 2007. More complex environments and tasks can be worked on from 2007 on.

The gap can be closed using the approach outlined for requirement i, but also taking advantage of developments in task management and scheduling from multi-agent systems, multi-computer operating systems and industrial automation systems.

#### 4.8.5.6 Requirement vi: Co-operative Perception: Ability to Share Data from Multiple Sources (Other Robots or Other Sensors)

2004 TRL: 5
2008 Feasibility: 3

This issue is a basic technology pre-requisite for the requirement described earlier as requirement iv “Co-operative Perception: to collectively recognise objects of interest” and has the same importance, approach and interdependencies.

For simple tasks (like direct communication) in structured environments this can be solved in 2005. More complex environments and tasks can be worked on from 2005 on.

#### 4.8.5.7 Requirement vii: To Interact with Other UGVs Performing Exactly the Same Task

2004 TRL: 4
2008 Feasibility: 3

This issue is in all respects as covered above in requirement i “To interact with other robots performing different, specialised tasks”. The difference is that here we require interaction between homogeneous

robots. It is thus a somewhat less demanding requirement and hence rates a higher 2004 TRL. This requirement needs to be achieved as a vital intermediate step in achieving the more complex task of interaction between heterogeneous robots.

The approach to be taken is as described for requirement i, above.

### 4.8.6 Issues Important but Not Vital to Close the Gap

#### 4.8.6.1 Requirement viii: Methodologies to Validate and Verify for Functionality, Reliability, and Safety of Multi-Robot Systems during Development

2004 TRL: 1
2008 Feasibility: 1

Military users apply very high quality standards to software and other development projects. The same must apply to multi-robot systems.

For all tasks (but especially those tasks where robots and humans closely interact, such as convoying or checkpoint operations) it is crucial that multi-robot systems operate in a provably reliable, predictable and safe manner. If not, the systems could well do more harm than good and, from a legal and social point of view, should not be used.

Work on this issue needs to start right away, as tools and methodologies for proving the dependability of multi-robot systems do not at present exist. These are, however, crucial for the development of multi-robot systems. This work should be finished by the end of 2005 as it is a foundation for further research. We can benefit from methods already developed for single robots, for example those developed by NASA and ESA.

The right approach would again be a European DARPA like organisation.

### 4.8.7 Longer-Term Issues

Following issue was discerned as a gap that will not influence the timely availability of a multi-robot system by 2008 for demonstration purposes (at the aimed TRL level 7). Nevertheless, this issue *is* important to have multi-robot systems accepted by users after 2008 and therefore should not be lost sight of.

#### 4.8.7.1 Requirement ix: Methodologies to Validate and Verify for Functionality, Reliability, and Safety of Multi-Robot Systems during Operations

2004 TRL: 1
2008 Feasibility: 1

For all tasks (but especially those tasks where robots and humans closely interact, such as convoying or checkpoint operations) it is crucial that multi-robot systems operate in a provably reliable, predictable and safe manner. If not, the systems could well do more harm than good and, from a legal and social point of view, should not be used.

The methods developed for research and development (requirement viii above) will need to be extended for methods to support operations. Some advantage might be taken from industrial transport systems. Work should start in 2006.

# Chapter 5 – CORE GROUP

At the end of the workshop the outcomes were discussed. Apart from the fact that system oriented roadmaps instead of technology oriented roadmaps would be of even greater value, it was acknowledged that the results of the workshop were of great value, both to the users and to the industry and researchers. The main benefit of the workshop was felt to be the bringing together of users and technology enablers, thus getting a better insight in each other's needs and possibilities.

In order to keep the integrating outcomes of the workshop alive, it was decided at the workshop to establish a so-called Core Group. This international group, consisting of users, industry and researchers, has committed herself to that task. Although the users initially consist of only military, other users that have related tasks are also invited to participate. For instance users like special forces or specific police units.

The Core Group is partially a NATO activity and partially a EURON activity. The NATO part focuses on supporting military-like tasks by robots while the EURON activity focuses on stimulating research to achieve goals relevant to the users and therefore the industry.

One of the main activities of this Core Group is the organization of a capability show, to be held in the second quarter of 2006. In the capability show, industry can display technology ready for actual production in a realistic users' scenario. The users even get the opportunity to manipulate the robots themselves for real hands-on experience exchange between industry and users. In a separate research contest which is to be held in 2007, the researchers can display the latest technology developments that are of value for the same scenario, but not yet at production stage. This information will be valuable for both industry and researchers.

Further details on the Core Group and its activities can be found on the website http://www.european-robotics.org.

# Chapter 6 – CONCLUSIONS

A gap in robotics between military users, industry and research actually does exist. This was recognized during the workshop organised September 2004 in Bonn, and was attended by over 70 participants from the military, industry, research and ministries from 16 different mainly European countries.

The gap between users and industry is caused partly by some ideas of military users on the way they would like to deploy robots for their tasks still needing to mature, and partly by the approach of industry of developing robots without very specifically digging into military specified needs and requirements.

The gap between industry and research is caused partly by industry not being aware of some developments going on in research and partly by research not being involved in and focused on real-life applications of military robots.

It was recognized during the workshop that this is the first time that this type of analysis on the gaps between user requirements and technical possibilities has been attempted. Essential in this was making the military tasks for which the users envisage the use of robotic support leading in the analysis.

Gaps do exist on all technological fields of interest that were discerned during the workshop:

1) Communication;
2) Robot platforms;
3) Sensing and world modelling;
4) Navigation and mission planning;
5) Human-robot interaction; and
6) Multi-robot systems.

Many gaps are essential to reach the goal set for the workshop, obtaining a system prototype demonstration in an operational environment for military use in the year 2008. This is equal to obtaining by that year an overall Technological Readiness Level (TRL) of 7 at least on all technological aspects relevant for such a military robot. A special field of interest is multi-robot systems which considers autonomous co-operation of multiple robots and thus exceeds the other five fields of interest but at the same time is not believed to be achievable by the year 2008.

Without closing the identified gaps, it will not be possible to have well usable robotic support for the military by 2008.

To close the gaps, many specific approaches for specific gaps were proposed but it was also advised to create a European version of the US DARPA, being a private/public co-operation. This organisation should lobby for funding and define research demands. The initiative for such a private/public co-operation should come from military users in the various countries, in mutual co-operation. This could be part of WEAG or OCCAR.

To start off closing the gap between users and industry / researchers, a so-called Core Group was formed during the workshop. One of the main activities of this Core Group, in pursuit of this goal, is the organization of a European military robotics Capability Show in the second quarter of 2006. Details on the Core Group and its activities can be found on the website http://www.european-robotics.org.

# Annex A – LIST OF TRL CODES

Following are the codes used during the workshop to express the Technology Readiness Levels (TRLs). These codes are generally accepted as a standard method to classify the level of technological development.

**TRL 9: Actual system "operationally / mission proven" through successful mission operations.**

Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Thoroughly debugged software. Fully integrated with operational hardware/software systems. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. All documentation completed. Successful operational experience. Sustaining software engineering support in place. Actual system fully demonstrated.

**TRL 8: Actual system completed and "operationally / mission qualified" through test and demonstration in an operational environment.**

Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification & Validation completed.

**TRL 7: System prototype demonstration in an operational environment.**

Prototype near or at planned operational system. Most functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Examples include testing the prototype in a test bed. Limited documentation available.

**TRL 6: System/subsystem prototype demonstration in a relevant end-to-end environment.**

Prototype implementations on full scale realistic problems. Partially integrated with existing hardware/software systems. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment. Limited documentation available. Engineering feasibility fully demonstrated.

**TRL 5: Module and/or subsystem validation in relevant environment.**

The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components. Prototype implementations conform to target environment / interfaces. Experiments with realistic problems. Simulated interfaces to existing systems.

**TRL 4: Module and/or subsystem validation in laboratory environment.**

Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory. Standalone prototype implementations. Experiments with full scale problems or data sets.

**TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept.**

Active research and development is initiated. Limited functionality implementations. Experiments with small representative data sets. Scientific feasibility fully demonstrated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.

**TRL 2: Technology concept and/or application formulated.**

Basic principles coded. Experiments with synthetic data. Mostly applied research. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.

**TRL 1: Basic principles observed and reported.**

Lowest level of technology readiness. Scientific research begins with to be translated into applied research and development. Mathematical formulations. Mix of basic and applied research. Example might include paper studies of a technology's basic properties.

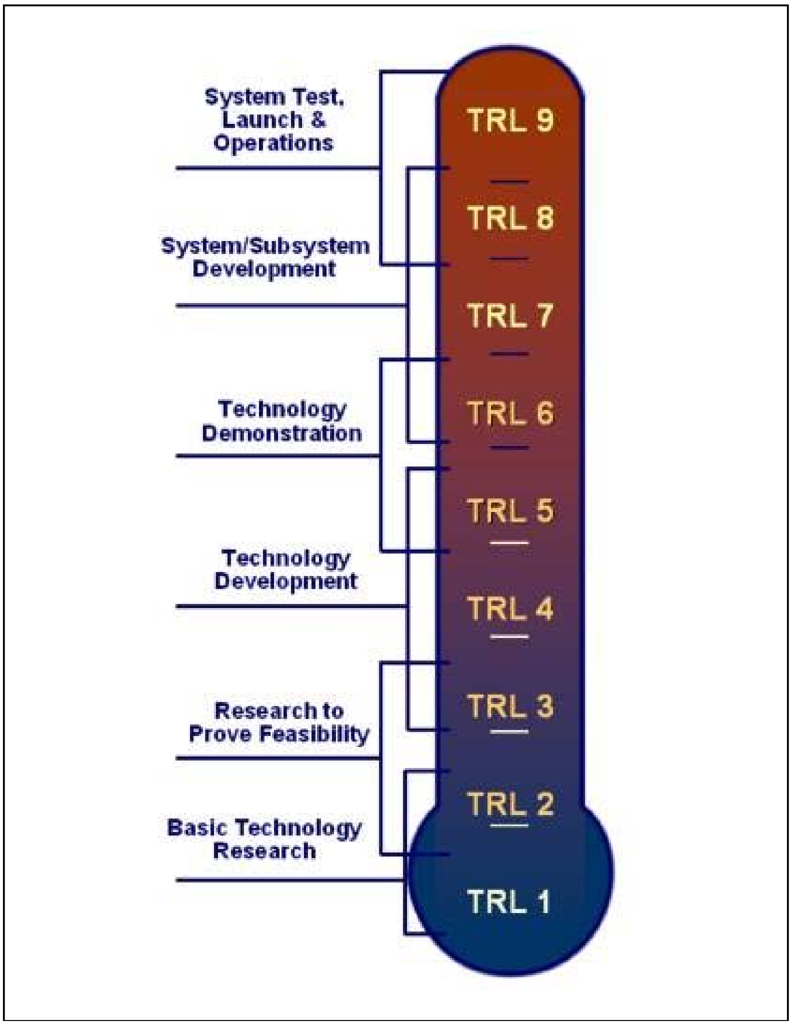


**Figure A-1: Interpretation of Technological Readiness Levels (TRLs).**

# Annex B – MILITARY TASKS AND USER REQUIREMENTS

This annex gives the military tasks that were generated and partly selected for further analysis during the workshop, and the operational requirements that the users stated for the five tasks that were selected as the most important ones.

The process used to find these tasks and user requirements is depicted in the figure below. In step 1, the military were asked to generate a list of tasks that they need to execute and for which they thought robotic support might be of some value. In step 2, the military were asked as potential future users of robots, to what extent they felt a robot could assist them in executing each of those tasks, varying from “not applicable” to “to a great extent”. Main reasons for a positive answer were assistance in the classic DDD (Dull, Dangerous, Dirty) tasks.

In step 3, the military selected from the best scored tasks a *hot list* of the five most desired tasks to have assisted by a robot. For each of these five most desired (or best) tasks the military were asked to indicate in step 4 the relevance of each potential user requirement in a pre-defined list of user requirements. The users were also allowed to extend the list with new user requirements if they felt one lacked.

In step 5, this list with the relevance of each user requirement for each of the five best tasks was handed over to the six technological groups. Here ends the information covered in this annex. The technology groups then continued to assess the requirements on feasibility and to determine gaps between user requirements and predicted future technological possibilities.

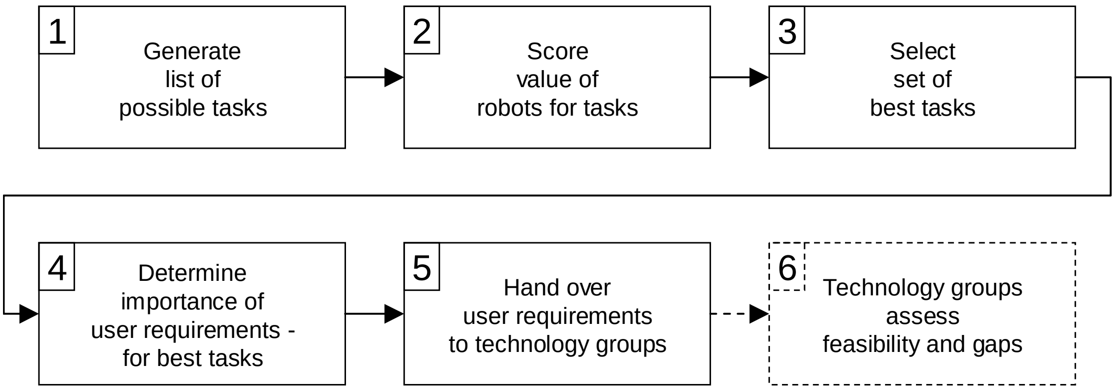


**Figure B-1: Process Used to Find Tasks and User Requirements.**

## B.1 MILITARY TASKS

Following is the list of tasks generated by the military users on the first day of the workshop, that might or might not be supported by robots. These tasks are also rated to the level to which the users thought support by robots would be valuable to the task. So, this list is the result of steps 1, 2 and 3 in the above figure.

To rate the relevance of each task, the scale in following scale was used:

| Points | Meaning |
|---|---|
| 9 | To a great extent |
| 3 | To some extent |
| 1 | To a small extent |
| 0 | Not applicable |

From these tasks, several ones were selected during the morning session of the first workshop day, to be used during the remainder of the workshop. For these tasks, shown with “Yes” in column “Selected” (see table below), the users specified their operational requirements in detail.

**Table B-1: Rated List of Tasks Generated by the Military Users**

| Points | Task | Selected |
|---|---|---|
| 9 | Carry equipment for dismounted soldier | Yes |
| 9 | Checking vehicles and people for explosives and weapons at checkpoints | Yes |
| 9 | Convoying- transport of goods | Yes |
| 9 | De-mining - clearing fields from AP and AT mines | Yes |
| 9 | De-mining – tactical | Yes |
| 9 | Detect NBC | Yes |
| 9 | Detecting and marking mines - both AT and AP | Yes |
| 9 | Reconnaissance in urban warfare | Yes |
| 9 | Surveillance and security - military camps and areas - compounds | Yes |
| 9 | De-mining- Tactical and post-conflict- clearing roads and fields from AP and AT mines | - |
| 9 | Reconnaissance and surveillance for tactical support for the forces on the ground including NBC | - |
| 3 | Countermeasures against robots | - |
| 3 | Decontaminate from NBC | - |
| 3 | Decoys and diversion | - |
| 3 | Detection of snipers | - |
| 3 | EOD - making explosive devices harmless | - |
| 3 | Information infrastructure | - |
| 3 | MEDEVAC | - |
| 3 | Recovering damaged vehicles and other materials | - |
| 3 | Refuelling and ammunition supply as Combat Service Support | - |
| 3 | Self-defence system for non-armoured vehicles and convoys | - |
| 3 | Self-mobile surveillance (e.g. flank protection) | - |
| 3 | Shooter for all calibres | - |
| 3 | Surveillance - wide area in open ground and long endurance | - |
| 3 | Surveillance- wide area in urban area and long endurance | - |
| 3 | Throwable robot for infantry | - |
| 3 | Underground vehicle for various tasks (listening, place mine, remove mine) | - |
| 1 | Breaching bushes - (tank) ditches | - |
| 1 | Clearing beach obstacles | - |
| 1 | Clearing snow and dirt from airfield runways | - |
| 1 | Information operation in urban terrain | - |
| 1 | Intelligent - moving minefield | - |

As the number of tasks to be elaborated during the remainder of the workshop was limited to five, but the military users were decisive to include all nine tasks marked with “Yes” in the table, the users decided to merge some of these nine tasks. A reason for them to do this was the notion that even though currently some of these nine tasks are distinct tasks, the users would prefer a robot that could be used for several of these tasks. This would for instance simplify technical support and maintenance, reduce the number of specialists to operate the robot, and reduce the total number of required robot systems.

The users merged these nine selected tasks into following five tasks:

1) Reconnaissance and surveillance for tactical support for the forces on the ground including NBC.

2) De-mining – Tactical and post-conflict – clearing roads and fields from AP and AT mines.
3) Convoying – transport of goods.
4) Checking vehicles and people for explosives and weapons at checkpoints.
5) Carry equipment for dismounted soldier.

These five tasks were used during the remainder of the workshop, and is the result of step 3 from the figure above.

## B.2 USER REQUIREMENTS

For the five selected tasks, the users specified the operational requirements in detail. So this is step 4 from the above figure.

These operational requirements are documented in the next sections. In these sections, it is specified per field of technology what importance the users gave to each and every operational requirement, for each of the five tasks.

These five tasks are numbered as stated above, so here are the task numbers and their meaning:

| Task number | Task |
|---|---|
| 1) | Reconnaissance and surveillance for tactical support for the forces on the ground including NBC. |
| 2) | De-mining - Tactical and post-conflict - clearing roads and fields from AP and AT mines. |
| 3) | Convoying - transport of goods. |
| 4) | Checking vehicles and people for explosives and weapons at checkpoints. |
| 5) | Carry equipment for dismounted soldier. |

The importance of a task is rated in the same way as the importance of the individual tasks was done. So, the following codes and meanings were used:

| Points | Meaning |
|---|---|
| 9 | To a great extent |
| 3 | To some extent |
| 1 | To a small extent |
| 0 | Not applicable |

### B.2.1 User Requirements on Communication

| Operational requirement on Communication | | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|---|
| Presence of wireless communication | | | | | | |
| | - with a range of 10 km | 9 | 9 | 9 | 9 | 9 |
| | - with a range of 25 km | 9 | 3 | 9 | 0 | 0 |
| | - with a range of 100 km | 9 | 1 | 9 | 0 | 0 |
| Safety of communication | | | | | | |
| | - protection against enemy parties understanding commands given to the UGV (enemy listening) | 9 | 9 | 9 | 9 | 9 |
| | - protection against enemy parties giving commands to the UGV (enemy sending) | 9 | 9 | 9 | 9 | 9 |

### B.2.2 User Requirements on Robot Platforms

| Operational requirement on Robot platforms | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|
| Preventing being spotted by enemies when UGV is stationary (not moving) | | | | | |
| - visible light at 1500 m distance from enemy | 9 | 1 | 0 | 0 | 9 |
| - infrared light at 1500 m distance from enemy | 9 | 1 | 0 | 0 | 9 |
| - radar at 1500 m distance from enemy | 9 | 1 | 0 | 0 | 9 |
| Preventing being spotted by enemies when UGV is moving | | | | | |
| - visible light at 1500 m distance from enemy | 9 | 1 | 0 | 0 | 9 |
| - infrared light at 1500 m distance from enemy | 9 | 1 | 0 | 0 | 9 |
| - radar at 1500 m distance from enemy | 9 | 1 | 0 | 0 | 9 |
| Limiting sound produced by UGV | | | | | |
| - fully operational system, stationary engines, light covered terrain, not audible beyond 50 meters | 9 | 0 | 3 | 0 | 9 |
| - fully operational system, stationary engines, light covered terrain, not audible beyond 200 meters | 9 | 0 | 9 | 0 | 9 |
| - fully operational system, driving at cruise speed, light covered terrain, not audible beyond 50 meters | 9 | 0 | 0 | 0 | 9 |
| - fully operational system, driving at cruise speed, light covered terrain, not audible beyond 200 meters | 9 | 0 | 3 | 0 | 9 |
| Limiting damage to UGV after hitting a mine | | | | | |
| - No mobility reducing damage due to Anti Personnel (AP) mine | 9 | 9 | 9 | 9 | 9 |
| - No mobility reducing damage due to Anti Tank (AT) mine of 10 kilogram | 9 | 9 | 3 | 0 | 0 |
| Possibility to move over asphalted roads | | | | | |
| - In flat terrain | 9 | 9 | 9 | 9 | 9 |
| - In lightly uneven terrain | 9 | 9 | 9 | 0 | 9 |
| - In highly uneven terrain | 9 | 9 | 9 | 0 | 9 |
| Possibility to ascend and descend a slope | | | | | |
| - of < 10% | 9 | 9 | 9 | 9 | 9 |
| - of 10..30% | 9 | 9 | 9 | 0 | 9 |
| - of 30..50% | 9 | 3 | 3 | 0 | 9 |
| - of 50..60% | 3 | 1 | 1 | 0 | 9 |
| - of > 60% | 3 | 0 | 1 | 0 | 9 |
| Possibility to drive parallel to a slope (transverse a slope) | | | | | |
| - of < 10% | 9 | 9 | 9 | 9 | 9 |
| - of 10..30% | 9 | 3 | 3 | 0 | 9 |
| - of 30..50% | 9 | 1 | 1 | 0 | 9 |
| - of > 50% | 9 | 1 | 0 | 0 | 9 |
| Possibility to pass through water | | | | | |
| - of 0.4..0.6 m depth | 9 | 9 | 9 | 0 | 9 |
| - of 0.6..0.8 m depth | 9 | 3 | 9 | 0 | 9 |
| - of 0.8..1.0 m depth | 9 | 3 | 9 | 0 | 9 |
| - of > 1.0 m depth | 9 | 0 | 1 | 0 | 9 |
| Possibility to cross step shaped barrier | | | | | |
| - of < 0.2 m | 9 | 9 | 9 | 0 | 9 |
| - of 0.3..0.4 m | 9 | 9 | 9 | 0 | 9 |
| - of 0.4..0.5 m | 9 | 0 | 3 | 0 | 9 |
| - of > 0.5 m | 9 | 1 | 1 | 0 | 9 |
| Possibility to cross barricade of debris / rubble / stones | | | | | |
| - of < 0.5 m height | 9 | 3 | 3 | 0 | 9 |
| - of 0.5..1.0 m height | 9 | 1 | 0 | 0 | 9 |
| - of > 1.0 m height | 9 | 0 | 0 | 0 | 9 |
| Possibility to cross deep trench / groove | | | | | |
| - of <0.4 m wide | 9 | 1 | 9 | 0 | 9 |
| - of 0.4..0.6 m wide | 9 | 1 | 3 | 0 | 9 |
| - of 0.6 m wide | 9 | 0 | 1 | 0 | 9 |
| Possibility to move forward in light terrain | | | | | |
| - at < 5 km/h | 9 | 9 | 9 | 9 | 9 |
| - at 5..20 km/h | 9 | 9 | 9 | 0 | 9 |
| - at 20..50 km/h | 9 | 3 | 9 | 0 | 0 |
| - at 50..70 km/h | 9 | 3 | 9 | 0 | 0 |
| - at > 70 km/h | 1 | 0 | 9 | 0 | 0 |
| Possibility to move forward in medium heavy terrain | | | | | |
| - at < 0.5 km/h | 9 | 9 | 9 | 9 | 9 |
| - at 0.5..2 km/h | 9 | 9 | 9 | 0 | 9 |
| - at 2..5 km/h | 9 | 9 | 3 | 1 | 9 |
| - at 5..10 km/h | 9 | 0 | 3 | 0 | 9 |
| - at > 10 km/h | 9 | 0 | 9 | 0 | 9 |

| Operational requirement on Robot platforms | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|
| Possibility to move forward in heavy terrain | | | | | |
| - at < 0.5 km/h | 9 | 9 | 9 | 0 | 9 |
| - at 0.5..2 km/h | 9 | 9 | 9 | 1 | 9 |
| - at 2..5 km/h | 3 | 1 | 3 | 1 | 9 |
| - at 5..10 km/h | 1 | 0 | 3 | 0 | 3 |
| - at > 10 km/h | 9 | 0 | 3 | 0 | 0 |
| Possibility to fire remotely controlled with the UGV by an operator | 9 | 1 | 3 | 9 | 0 |
| Possibility to supply all systems with required energy while the UGV's engine is not running | | | | | |
| - for < 1 hour | 9 | 9 | 9 | 9 | 9 |
| - for 1..3 hours | 9 | 0 | 1 | 3 | 9 |
| - for 3..5 hours | 9 | 0 | 1 | 3 | 3 |
| - for 5..7 hours | 3 | 0 | 0 | 0 | 0 |
| - for > 7 hours | 9 | 0 | 0 | 0 | 0 |
| Possibility to use UGV under climatic circumstances | | | | | |
| - moderate | 9 | 9 | 9 | 9 | 9 |
| - tropical (hot and wet) | 9 | 9 | 9 | 9 | 9 |
| - desert (hot and dry) | 9 | 9 | 9 | 9 | 9 |
| - polar | 9 | 3 | 3 | 3 | 9 |
| Endurance when used for task | | | | | |
| - < 24 hours | 9 | 9 | 9 | 9 | 9 |
| - 24..48 hours | 9 | 3 | 9 | 9 | 9 |
| - 2..5 days | 3 | 1 | 3 | 1 | 3 |
| - > 5 days | 1 | 1 | 1 | 1 | 1 |
| Range (inbound and outbound summed up) | | | | | |
| - < 10 km | 9 | 9 | 9 | 9 | 9 |
| - 10..50 km | 9 | 3 | 9 | 1 | 9 |
| - 50..150 km | 9 | 1 | 9 | 0 | 3 |
| - 150..300 km | 3 | 0 | 9 | 0 | 0 |
| - > 300 km | 1 | 0 | 9 | 0 | 0 |

### B.2.3 User Requirements on Sensing and World Modelling

| Operational requirement on Sensing and world modelling | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|
| Usability vision systems under light conditions | | | | | |
| - Blazing sunshine | 9 | 9 | 9 | 9 | 9 |
| - Dense mist | 9 | 9 | 9 | 9 | 9 |
| - Darkness | 9 | 9 | 9 | 9 | 9 |
| - Snow on the ground (currently not snowing) | 9 | 9 | 9 | 9 | 9 |
| Usability vision systems under precipitation conditions | | | | | |
| - Light rain | 9 | 9 | 9 | 9 | 9 |
| - Heavy rain | 9 | 9 | 9 | 9 | 9 |
| - Light snowing | 9 | 9 | 9 | 9 | 9 |
| - Heavy snowing | 9 | 9 | 9 | 9 | 9 |
| Possibility to observe up to 90 degrees around | | | | | |
| - in vertical sector with lower boundary of < -15 degrees | 9 | 9 | 3 | 9 | 3 |
| - in vertical sector with lower boundary of -15..-10 degrees | 9 | 0 | 0 | 9 | 0 |
| - in vertical sector with lower boundary of -10..-5 degrees | 9 | 0 | 0 | 9 | 9 |
| - in vertical sector with lower boundary of -5..0 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector with lower boundary of 0 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector with lower boundary of > 0 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector met upper boundary of < 0 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector met upper boundary of 0..15 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector met upper boundary of 15..30 degrees | 9 | 0 | 0 | 0 | 0 |
| - in vertical sector met upper boundary of > 30 degrees | 9 | 0 | 0 | 0 | 0 |
| Possibility to observe up to 120 degrees around | | | | | |
| - in vertical sector with lower boundary of < -15 degrees | 9 | 9 | 3 | 9 | 9 |
| - in vertical sector with lower boundary of -15..-10 degrees | 9 | 0 | 0 | 0 | 0 |
| - in vertical sector with lower boundary of -10..-5 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector with lower boundary of -5..0 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector with lower boundary of 0 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector with lower boundary of > 0 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector met upper boundary of < 0 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector met upper boundary of 0..15 degrees | 9 | 0 | 0 | 0 | 9 |
| - in vertical sector met upper boundary of 15..30 degrees | 9 | 0 | 0 | 0 | 0 |
| - in vertical sector met upper boundary of > 30 degrees | 9 | 0 | 3 | 0 | 9 |

| Operational requirement on Sensing and world modelling | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|
| Possibility of autonomous obstacle avoidance on commanded routes | | | | | |
| - of pit holes of < 1 m wide and < 1 m long | 9 | 3 | 9 | 0 | 9 |
| - of water pools in road of < 1 m wide and < 1 m long | 9 | 9 | 9 | 1 | 9 |
| - of vegetation (bushes) on road of < 1 m high and < 0.5 m wide | 9 | 3 | 9 | 1 | 9 |
| - of stones and/or metal on road of < 1 m high and < 0.5 m wide | 9 | 9 | 9 | 1 | 9 |
| Possibility to detect Anti Personnel (AP) mines | | | | | |
| - chance of not detecting a present AP mine < 1% | 9 | 9 | 1 | 0 | 0 |
| - chance of not detecting a present AP mine 1..5% | 9 | 9 | 1 | 0 | 0 |
| - chance of not detecting a present AP mine 5..10% | 9 | 9 | 1 | 0 | 0 |
| - chance of not detecting a present AP mine >10% | 9 | 9 | 0 | 0 | 0 |
| - chance of falsely detecting a non-present AP mine < 1% | 1 | 9 | 1 | 0 | 0 |
| - chance of falsely detecting a non-present AP mine 1..5% | 1 | 9 | 1 | 0 | 0 |
| - chance of falsely detecting a non-present AP mine 5..10% | 1 | 9 | 0 | 0 | 0 |
| - detection width < 3 m | 0 | 9 | 0 | 0 | 0 |
| - detection width 3..5 m | 0 | 9 | 0 | 0 | 0 |
| - detection width > 5 m | 0 | 9 | 0 | 0 | 0 |
| - detection AP mine on surface | 9 | 9 | 0 | 0 | 0 |
| - detection AP mine at 1..10 cm depth | 0 | 9 | 0 | 0 | 0 |
| - detection AP mine at > 10 cm depth | 0 | 9 | 0 | 0 | 0 |
| Possibility to detect Anti Tank (AT) mines | | | | | |
| - chance of not detecting a present AT mine < 1% | 0 | 9 | 0 | 0 | 0 |
| - chance of not detecting a present AT mine 1..5% | 3 | 9 | 1 | 0 | 0 |
| - chance of not detecting a present AT mine 5..10% | 9 | 9 | 1 | 0 | 0 |
| - chance of not detecting a present AT mine >10% | 9 | 9 | 0 | 0 | 0 |
| - chance of falsely detecting a non-present AT mine < 1% | 9 | 9 | 0 | 0 | 0 |
| - chance of falsely detecting a non-present AT mine 1..5% | 1 | 9 | 1 | 0 | 0 |
| - chance of falsely detecting a non-present AT mine 5..10% | 9 | 9 | 0 | 0 | 0 |
| - detection width < 3 m | 0 | 9 | 0 | 0 | 0 |
| - detection width 3..5 m | 0 | 9 | 0 | 0 | 0 |
| - detection width > 5 m | 0 | 9 | 0 | 0 | 0 |
| - detection AT mine on surface | 9 | 9 | 0 | 0 | 0 |
| - detection AT mine at 1..10 cm depth | 0 | 9 | 0 | 0 | 0 |
| - detection AT mine at > 10 cm depth | 0 | 9 | 0 | 0 | 0 |
| Possibility to autonomously generate firing <u>request</u> (but no autonomous firing by the UGV itself) | 9 | 0 | 0 | 0 | 0 |
| Possibility to detect (i.e. see that it is there) targets under average visibility circumstances | | | | | |
| - alighted personnel at distances > 500 m | 9 | 0 | 3 | 1 | 9 |
| - alighted personnel at distances > 1000 m | 9 | 0 | 1 | 0 | 0 |
| - alighted personnel at distances > 1500 m | 9 | 0 | 1 | 0 | 0 |
| - individual vehicles at distances >1000 m | 9 | 0 | 0 | 1 | 0 |
| - individual vehicles at distances > 2000 m | 9 | 0 | 1 | 0 | 0 |
| - individual vehicles at distances > 3000 m | 9 | 0 | 1 | 0 | 0 |
| Possibility to recognize (i.e. see what it is) targets under average visibility circumstances | | | | | |
| - alighted personnel at distances > 500 m | 9 | 0 | 3 | 1 | 9 |
| - alighted personnel at distances > 1000 m | 9 | 0 | 1 | 0 | 0 |
| - alighted personnel at distances > 1500 m | 9 | 0 | 0 | 0 | 0 |
| - individual vehicles at distances >1000 m | 9 | 0 | 1 | 0 | 0 |
| - individual vehicles at distances > 2000 m | 9 | 0 | 1 | 0 | 0 |
| - individual vehicles at distances > 3000 m | 9 | 0 | 0 | 0 | 0 |
| Possibility to identify (i.e. see who it is) targets under average visibility circumstances | | | | | |
| - alighted personnel at distances > 500 m | 9 | 0 | 1 | 0 | 0 |
| - alighted personnel at distances > 1000 m | 9 | 0 | 0 | 0 | 0 |
| - alighted personnel at distances > 1500 m | 9 | 0 | 1 | 0 | 0 |
| - individual vehicles at distances >1000 m | 9 | 1 | 1 | 0 | 0 |
| - individual vehicles at distances > 2000 m | 9 | 1 | 0 | 0 | 0 |
| - individual vehicles at distances > 3000 m | 9 | 1 | 1 | 1 | 0 |
| Possibility to detect (i.e. see that it is there) targets under less visibility circumstances | | | | | |
| - alighted personnel at distances >100 m | 9 | 0 | 3 | 0 | 0 |
| - alighted personnel at distances > 250 m | 9 | 0 | 0 | 0 | 0 |
| - alighted personnel at distances > 500 m | 9 | 0 | 3 | 0 | 0 |
| - individual vehicles at distances >1000 m | 9 | 0 | 3 | 0 | 0 |
| - individual vehicles at distances > 2000 m | 9 | 0 | 0 | 0 | 0 |
| - individual vehicles at distances > 3000 m | 9 | 0 | 1 | 0 | 0 |
| Possibility to recognize (i.e. see what it is) targets under less visibility circumstances | | | | | |
| - alighted personnel at distances >50 m | 9 | 0 | 3 | 0 | 0 |
| - alighted personnel at distances > 100 m | 9 | 0 | 0 | 0 | 0 |
| - alighted personnel at distances > 250 m | 9 | 0 | 0 | 0 | 0 |
| - individual vehicles at distances >1000 m | 9 | 0 | 0 | 0 | 0 |

| Operational requirement on Sensing and world modelling | | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|---|
| | - individual vehicles at distances > 2000 m | 9 | 0 | 0 | 0 | 0 |
| | - individual vehicles at distances > 3000 m | 9 | 0 | 0 | 0 | 0 |
| Possibility to identify (i.e. see who it is) targets under less visibility circumstances | | | | | | |
| | - alighted personnel at distances > 50 m | 9 | 0 | 3 | 0 | 0 |
| | - alighted personnel at distances > 100 m | 9 | 0 | 0 | 0 | 0 |
| | - alighted personnel at distances > 250 m | 9 | 0 | 0 | 0 | 0 |
| | - individual vehicles at distances >1000 m | 9 | 0 | 0 | 0 | 0 |
| | - individual vehicles at distances > 2000 m | 9 | 0 | 0 | 0 | 0 |
| | - individual vehicles at distances > 3000 m | 9 | 0 | 0 | 0 | 0 |
| Possibility to follow moving targets | | | | | | |
| | - at target moving speed of < 20 km/h | 9 | 0 | 0 | 0 | 0 |
| | - at target moving speed of 20..50 km/h | 9 | 0 | 0 | 0 | 0 |
| | - at target moving speed of 50..100 km/h | 9 | 0 | 0 | 0 | 0 |
| | - at target moving speed of > 100 km/h | 9 | 0 | 0 | 0 | 0 |
| | - at viewing angle change speed < 5 degrees/s | 9 | 0 | 0 | 0 | 0 |
| | - at viewing angle change speed 5..15 degrees/s | 9 | 0 | 0 | 0 | 0 |
| | - at viewing angle change speed 15..30 degrees/s | 9 | 0 | 0 | 0 | 0 |
| | - at viewing angle change speed > 30 degrees/s | 9 | 0 | 0 | 0 | 0 |

## B.2.4 User Requirements on Navigation and Mission Planning

| Operational requirement on Navigation and mission planning | | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|---|
| Possibility of alternative routes if the commanded route does not work | | | | | | |
| | - autonomous alternative route determination | 9 | 0 | 9 | 0 | 9 |
| | - fully manual alternative route determination by the operator | 9 | 0 | 9 | 0 | 9 |
| | - autonomous alternative route determination, with possibility for the operator to overrule | 9 | 9 | 9 | 9 | 9 |
| Possibility to follow roads | | | | | | |
| | - dirt road | 9 | 9 | 9 | 9 | 9 |
| | - brick road | 9 | 9 | 9 | 9 | 9 |
| | - asphalt road | 9 | 9 | 9 | 9 | 9 |
| Possibility to follow vehicles (convoy) | | | | | | |
| | - leader vehicle can be specific type only (e.g. possibility to follow specific military vehicle type only) | 0 | 0 | 9 | 0 | 0 |
| | - leader vehicle can be any type (e.g. possibility to follow any civil or military vehicle type that is available) | 9 | 0 | 9 | 0 | 0 |
| | - leader vehicle that is man driven | 0 | 0 | 9 | 0 | 0 |
| | - leader vehicle that is autonomous | 0 | 0 | 9 | 0 | 0 |
| Possibility to drive in mixed traffic (UGV within normal traffic) | | | | | | |
| | - at < 5 km/h | 9 | 9 | 9 | 0 | 9 |
| | - at 5..20 km/h | 9 | 0 | 9 | 0 | 9 |
| | - at 20..50 km/h | 9 | 0 | 9 | 0 | 3 |
| | - at 50..70 km/h | 3 | 0 | 9 | 0 | 0 |
| | - at > 70 km/h | 9 | 0 | 9 | 0 | 0 |
| Possibility to drive in crowed streets (urban terrain) | | 9 | 1 | 9 | 0 | 9 |
| Possibility to autonomously navigate along a route with maximum cover | | 9 | 1 | 9 | 0 | 9 |
| Possibility to autonomously navigate along a route avoiding hostile fire | | 9 | 0 | 9 | 0 | 9 |
| Possibility to autonomously navigate through vegetation | | | | | | |
| | - high grass | 9 | 9 | 9 | 0 | 9 |
| | - sparse bushes of < 0.5 m high | 9 | 9 | 9 | 0 | 9 |
| | - sparse bushes of < 1 m high | 9 | 9 | 3 | 0 | 9 |
| | - sparse bushes of > 1 m high | 9 | 9 | 3 | 0 | 9 |
| | - dense bushes of < 0.5 m high | 9 | 9 | 3 | 0 | 9 |
| | - dense bushes of < 1 m high | 9 | 9 | 3 | 0 | 9 |
| | - dense bushes of > 1 m high | 9 | 9 | 3 | 0 | 9 |

## B.2.5 User Requirements on Human-Robot Interaction

| Operational requirement | | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|---|
| Initial training effort required for mastering basic UGV control for non-expert. | | | | | | |
| | < 1 hour | 9 | 9 | 9 | 9 | 9 |
| | < 8 hours | 1 | 9 | 3 | 9 | 9 |
| | < 1 week | 3 | 9 | 9 | 0 | 0 |

| Operational requirement | | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|---|
| | < 2 weeks | 9 | 9 | 9 | 0 | 0 |
| | < 1 month | 9 | 0 | 0 | 0 | 0 |
| Training effort required for basic UGV control for trained personnel to maintain required skill level | | | | | | |
| | < 1 hour per month | 9 | 3 | 9 | 3 | 9 |
| | < 1 hour per week | 9 | 9 | 9 | 9 | 9 |
| | < 8 hours per month | 0 | 0 | 0 | 0 | 0 |
| | < 8 hours per week | 0 | 0 | 0 | 0 | 0 |
| Workload/Occupation level for operator performing basic UGV control in simple terrain | | | | | | |
| | < 25 % | 9 | 9 | 9 | 9 | 9 |
| | < 50 % | 3 | 0 | 3 | 9 | 3 |
| | < 75 % | 9 | 9 | 9 | 0 | 9 |
| Workload/Occupation level for operator performing basic UGV control in difficult terrain | | | | | | |
| | < 25 % | 9 | 9 | 9 | 0 | 9 |
| | < 50 % | 9 | 9 | 9 | 0 | 9 |
| | < 75 % | 9 | 0 | 0 | 0 | 9 |
| Possibility to substitute/support UGV operator training/instructing using interactive simulations | | | | | | |
| | - for basic UGV control and maneuvering | 9 | 9 | 9 | 9 | 9 |
| | - for payload related control | 9 | 9 | 9 | 9 | 9 |
| Possibility to evaluate the performance of the human-robot team | | 9 | 9 | 9 | 9 | 9 |
| Possibility to define measures of effectiveness for the human-robot team | | 9 | 9 | 9 | 9 | 9 |
| Possibility of consistent interface design for different UGVs for common UGV functions (on/off, maneuvering, parking etc.) | | | | | | |
| | - standardized controls (e.g. Maneuvering) | 9 | 9 | 9 | 9 | 9 |
| | - standardized symbolic representation (e.g. ISO, DIN, MIL based symbols) | 9 | 9 | 9 | 9 | 9 |
| | - standardized layout or sub-layouts for interface components | 9 | 9 | 9 | 9 | 9 |
| Possibility to integrate user interface into existing IT equipment | | | | | | |
| | - integration into existing equipment | 9 | 9 | 9 | 9 | 9 |
| | - integration into planned equipment | 9 | 9 | 9 | 9 | 9 |
| Possibility to provide robot execution plan to operator | | | | | | |
| | - ahead of mission | 9 | 9 | 9 | 9 | 9 |
| | - ahead of maneuver | 9 | 9 | 9 | 9 | 9 |
| | - in real time (online) | 9 | 9 | 9 | 9 | 9 |
| | - after execution | 9 | 9 | 9 | 9 | 9 |
| Possibility to estimate/measure/predict UGV performance | | | | | | |
| | - ahead of mission | 9 | 9 | 9 | 9 | 9 |
| | - ahead of maneuver | 9 | 3 | 3 | 3 | 3 |
| | - in real time (online) | 9 | 9 | 9 | 9 | 9 |
| | - after execution | 9 | 9 | 9 | 9 | 9 |
| Possibility to share UGV control between multiple operators | | 3 | 3 | 9 | 9 | 9 |
| Possibility to have one operator control multiple UGVs in a serial setting (only one UGV active at a time) | | | | | | |
| | # 2 | 3 | 9 | 9 | 1 | 1 |
| | # 4 | 3 | 9 | 9 | 1 | 0 |
| | # 6 | 3 | 9 | 9 | 1 | 0 |
| | # 8 | 3 | 9 | 9 | 1 | 0 |
| Possibility to have one operator control multiple UGVs in a concurrent setting (all UGVs can be active) | | | | | | |
| | # 2 | 1 | 9 | 9 | 1 | 1 |
| | # 4 | 3 | 9 | 9 | 1 | 0 |
| | # 6 | 3 | 3 | 9 | 1 | 0 |
| | # 8 | 3 | 1 | 9 | 1 | 0 |
| Possibility to scale operator to robot ratio on demand (adapting to unexpected workload peaks) | | 9 | 9 | 9 | 9 | 9 |
| Possibility to integrate UGV and payload control into a single operator interface | | 9 | 9 | 9 | 9 | 9 |
| Interaction limitations caused by UGV loosing line of sight (LOS) contact with operator | | | | | | |
| | - no limitations | 9 | 9 | 9 | 9 | 9 |
| | - LOS functionality replaced/covered by redundant non-LOS functions | 9 | 3 | 9 | 0 | 9 |
| | - LOS functionality partially replaced by non-LOS functions | 3 | 3 | 9 | 3 | 3 |
| | - loss of LOS functionality | 0 | 0 | 0 | 0 | 0 |
| Levels of mobility for control station having at least an 800x600 color display and pointing and text entering capability | | | | | | |
| | - stationary installation | 9 | 9 | 9 | 9 | 0 |
| | - vehicle based installation | 9 | 9 | 9 | 9 | 0 |
| | - vehicle based, can be used while vehicle is moving | 9 | 9 | 9 | 9 | 0 |
| | - stationary but man-portable | 9 | 9 | 9 | 9 | 9 |
| | - wearable, requiring an operator to interrupt other activities (e.g. Moving) | 9 | 0 | 0 | 0 | 9 |
| | - wearable, can be used while performing other activities (e.g. Head-mounted display, voice controlled) | 9 | 0 | 0 | 9 | 9 |

| Operational requirement | | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|---|
| Required setup time until operational for control station having at least an 800x600 color display and pointing and text entering capability | | | | | | |
| | - always on, mobile, no setup time required | 9 | 0 | 0 | 0 | 1 |
| | - minimal setup time (e.g. Boot time) | 9 | 0 | 0 | 0 | 9 |
| | < 1 minute | 9 | 3 | 0 | 9 | 9 |
| | < 30 minutes | 0 | 9 | 9 | 0 | 0 |
| | < 1 hour | 0 | 0 | 0 | 0 | 0 |
| Degradation of performance (e.g. speed, accuracy) for basic UGV control when operator is wearing protective gloves | | | | | | |
| | - no degradation | 9 | 9 | 9 | 9 | 9 |
| | < 25 % | 9 | 0 | 0 | 0 | 0 |
| | < 50 % | 0 | 0 | 0 | 0 | 0 |
| | < 75 % | 0 | 0 | 0 | 0 | 0 |
| Degradation of performance (e.g. speed, accuracy) for basic UGV control when operator is wearing protective vest | | | | | | |
| | - no degradation | 9 | 9 | 9 | 9 | 9 |
| | < 25 % | 0 | 0 | 0 | 0 | 0 |
| | < 50 % | 0 | 0 | 0 | 0 | 0 |
| | < 75 % | 0 | 0 | 0 | 0 | 0 |
| Degradation of performance (e.g. speed, accuracy) for basic UGV control when operator is wearing full ABC protection | | | | | | |
| | - no degradation | 9 | 9 | 9 | 9 | 9 |
| | < 25 % | 9 | 3 | 0 | 3 | 3 |
| | < 50 % | 0 | 0 | 0 | 9 | 0 |
| | < 75 % | 0 | 0 | 0 | 0 | 0 |
| Achievable level of precision in simple terrain for entering/modifying commands within 10m radius of robot | | | | | | |
| | < 0.01m | 1 | 0 | 1 | 0 | 0 |
| | < 0.1m | 3 | 9 | 0 | 9 | 0 |
| | < 0.5m | 9 | 9 | 9 | 9 | 9 |
| | < 1m | 9 | 0 | 9 | 0 | 9 |
| Achievable level of precision in simple terrain for entering/modifying commands within 50m radius of robot | | | | | | |
| | < 0.01m | 1 | 0 | 1 | 0 | 0 |
| | < 0.1m | 3 | 9 | 3 | 9 | 0 |
| | < 0.5m | 9 | 9 | 0 | 0 | 9 |
| | < 1m | 9 | 9 | 9 | 9 | 9 |
| | < 5m | 0 | 0 | 0 | 0 | 0 |
| Possibility to realise mobile human robot interface using COTS products (e.g. Laptops, | | 9 | 9 | 9 | 9 | 9 |
| Possibility to add, modify or delete elements of the UGVs internal world representation | | 9 | 9 | 9 | 9 | 9 |
| Possibility to interact deviceless with robot (e.g. Pointing gestures) | | 1 | 1 | 1 | 1 | 1 |
| Possibility to provide robot command interpretation feedback to enable online command verification | | 9 | 3 | 3 | 0 | 3 |
| Possibility to provide robot command execution projection to enable online command execution supervision | | 9 | 9 | 0 | 0 | 0 |
| Possibility to create/edit/delete waypoints | | 9 | 9 | 9 | 9 | 9 |

### B.2.6 User Requirements on Multi-Robot Systems

| Operational requirement on Multi-robot systems | | Task 1 | Task 2 | Task 3 | Task 4 | Task 5 |
|---|---|---|---|---|---|---|
| Possibility to interact with other robots | | | | | | |
| | - exchange map information between UGV's | 9 | 9 | 9 | 3 | 9 |
| | - exchange target observation information between UGV's | 9 | 9 | 9 | 1 | 9 |
| | - perform a task with multiple, collaborative UGV's | 9 | 9 | 9 | 3 | 9 |
| | - autonomously divide a task, specified by the operator, between several UGV's | 9 | 9 | 9 | 3 | 9 |
| | - interact with other UGV's performing exactly the same task | 9 | 9 | 9 | 1 | 9 |
| | - interact with other UGV's performing different, specialised tasks | 9 | 9 | 9 | 9 | 9 |

# Annex C – CURRENT TECHNOLOGICAL STATUS

Following is the current status of the six fields of technological interest, as stated during the workshop. The current status (i.e. in the year 2004) of the various operational requirements is expressed in terms of a TRL code as explained in Annex A.

## C.1 COMMUNICATION

The TRL codes indicating the 2004 status for all communication related user requirements are shown in the table below.

| | TRL |
|---|---|
| | TRL Code [1..9] |
| **Operational requirement** | |
| Presence of wireless communication | |
| - with a range of 10 km | 7 |
| - with a range of 25 km | 3 |
| - with a range of 100 km | 3 |
| Safety of communication | |
| - protection against enemy parties understanding commands given to the UGV (enemy listening) | 9 |
| - protection against enemy parties giving commands to the UGV (enemy sending) | 9 |
| Safety of communication | |
| - intrusion detection / prevention | 3 |
| - protection against jamming | 6 |
| - authentication of robot data, esp. pictures/video | 4 |
| Adaptive communication | |
| - spectrum monitoring | 9 |
| - spectrum management | 9 |
| - reconfigurability of the communications network | 4-5 |
| Autoconfiguration of a network (around 50 nodes) | |
| - autoconfiguration within 10 minutes | 2 |
| - autoconfiguration within 1 hour | 3 |
| - autoconfiguration within some hours | 3 |
| Presence of wireless communication | |
| - with a range of 100m (inside buildings) | 6 |
| - with a range of 1km (urban area) | 6 |
| Presence of wireless communication | |
| - multipoint communication with a range of 100 m and high bitrate | 3 |
| - multipoint communication with a range of 100 m and low bitrate | 4 |
| - multipoint communication with a range of 1 km and high bitrate | 2-3 |
| - multipoint communication with a range of 1 km and low bitrate | 3 |
| - point-to-point communication with a range of 100 m and high bitrate | 9 |
| - point-to-point communication with a range of 100 m and low bitrate | 9 |
| - point-to-point communication with a range of 1 km and high bitrate | 7 |
| - point-to-point communication with a range of 1 km and low bitrate | 8 |
| - point-to-point communication with a range of 10 km and high bitrate | 6 |
| - point-to-point communication with a range of 10 km and low bitrate | 7 |
| Bandwidth requirements in multipoint comm. like wireless LAN | |
| - high-quality video at 25fps (real-time) | 1 |

| Operational requirement | TRL<br>TRL Code [1..9] |
|---|---|
| - high-quality video at 10fps | 1 |
| - high-quality video at 1fps | 4 |
| - high-quality still pictures | 6 |
| - low-quality video at 25fps (real-time) | 1 |
| - low-quality video at 10fps | 1 |
| - low-quality video at 1fps | 6 |
| - low-quality still pictures | 7 |
| - real-time audio transmission | 6 |
| Inter-robot communication | |
| - communication for robot cooperation based on sensor data | 4 |
| - communication for relaying | 6 |
| Implications of environmental conditions on communications | |
| - works under very wet environment (heavy rain, thunderstorm) | 7 |
| - works in very dusty environment (sand storm) | 6 |
| - works in very hot environment (burning) | 3 |
| - works in hot environment (55 °C) | 9 |
| - works in cold environment (-20°C) | 9 |
| - works in radioactive environment | 2 |
| Implications of terrain | |
| - open area | 9 |
| - unstructured area | 7 |
| - urban area | 7 |

## C.2 ROBOT PLATFORMS

The TRL codes indicating the 2004 status for all robot platform related user requirements are shown in the table below.

| Operational requirement | | TRL<br>TRL Code [1..9] |
|---|---|---|
| Preventing being spotted by enemies when UGV is stationary (not moving) | | |
| | - visible light at 1500 m distance from enemy | 9 |
| | - infrared light at 1500 m distance from enemy | 2 |
| | - radar at 1500 m distance from enemy | 1 |
| Preventing being spotted by enemies when UGV is moving | | |
| | - visible light at 1500 m distance from enemy | 1 |
| | - infrared light at 1500 m distance from enemy | 1 |
| | - radar at 1500 m distance from enemy | 1 |
| Limiting sound produced by UGV | | |
| | - fully operational system, stationary engines, light covered terrain, not audible beyond 50 meters | 9 |
| | - fully operational system, stationary engines, light covered terrain, not audible beyond 200 meters | 9 |
| | - fully operational system, driving at cruise speed, light covered terrain, not audible beyond 50 meters | 7 |
| | - fully operational system, driving at cruise speed, light covered terrain, not audible beyond 200 meters | 9 |
| Limiting damage to UGV after hitting a mine | | |
| | - No mobility reducing damage due to Anti Personnel (AP) mine | 9 |

| | | TRL |
|---|---|---|
| | | **TRL Code [1..9]** |
| **Operational requirement** | | |
| | - No mobility reducing damage due to Anti Tank (AT) mine of 10 kilogram | 5 |
| Possibility to move over asphalted roads | | |
| | - In flat terrain | 9 |
| | - In lightly uneven terrain | 9 |
| | - In highly uneven terrain | 9 |
| Possibility to ascend and descend a slope | | |
| | - of < 10% | 9 |
| | - of 10..30% | 9 |
| | - of 30..50% | 9 |
| | - of 50..60% | 8 |
| | - of > 60% | 6 |
| Possibility to drive parallel to a slope (transverse a slope) | | |
| | - of < 10% | 9 |
| | - of 10..30% | 9 |
| | - of 30..50% | 9 |
| | - of > 50% | 6 |
| Possibility to pass through water | | |
| | - of 0.4..0.6 m depth | 9 |
| | - of 0.6..0.8 m depth | 9 |
| | - of 0.8..1.0 m depth | 9 |
| | - of > 1.0 m depth | 9 |
| Possibility to cross step shaped barrier | | |
| | - of < 0.2 m | 9 |
| | - of 0.3..0.4 m | 8 |
| | - of 0.4..0.5 m | 7 |
| | - of > 0.5 m | 6 |
| Possibility to cross barricade of debris / rubble / stones | | |
| | - of < 0.5 m height | 9 |
| | - of 0.5..1.0 m height | 8 |
| | - of > 1.0 m height | 7 |
| Possibility to cross deep trench / groove | | |
| | - of <0.4 m wide | 9 |
| | - of 0.4..0.6 m wide | 9 |
| | - of 0.6 m wide | 9 |
| Possibility to move forward in light terrain | | |
| | - at < 5 km/h | 9 |
| | - at 5..20 km/h | 9 |
| | - at 20..50 km/h | 7 |
| | - at 50..70 km/h | 6 |
| | - at > 70 km/h | 6 |
| Possibility to move forward in medium heavy terrain | | |
| | - at < 0.5 km/h | 9 |
| | - at 0.5..2 km/h | 9 |
| | - at 2..5 km/h | 6 |
| | - at 5..10 km/h | 6 |
| | - at > 10 km/h | 6 |
| Possibility to move forward in heavy terrain | | |
| | - at < 0.5 km/h | 9 |

| Operational requirement | | TRL<br>TRL Code [1..9] |
|---|---|---|
| | - at 0.5..2 km/h | 9 |
| | - at 2..5 km/h | 6 |
| | - at 5..10 km/h | 4 |
| | - at > 10 km/h | 4 |
| Possibility to fire remotely controlled with the UGV by an operator | | 7 |
| | | |
| Possibility to supply all systems with required energy while the UGV's engine is not running | | |
| | - for < 1 hour | 9 |
| | - for 1..3 hours | 9 |
| | - for 3..5 hours | 9 |
| | - for 5..7 hours | 7 |
| | - for > 7 hours | 7 |
| Possibility to use UGV under climatic circumstances | | |
| | - moderate | 9 |
| | - tropical (hot and wet) | 6 |
| | - desert (hot and dry) | 7 |
| | - polar | 3 |
| Endurance when used for task | | |
| | - < 24 hours | 9 |
| | - 24..48 hours | 6 |
| | - 2..5 days | 3 |
| | - > 5 days | 3 |
| Range (inbound and outbound summed up) | | |
| | - < 10 km | 9 |
| | - 10..50 km | 7 |
| | - 50..150 km | 7 |
| | - 150..300 km | 6 |
| | - > 300 km | 6 |
| Weight | | |
| | - < 15 kg | 7 |
| | - 15..30 kg | 9 |
| | - 30..100 kg | 9 |
| | - 100..250 kg | 9 |
| | - > 250 kg | 9 |
| | | |
| Capability of climbing a generic (non standard step) flight of stairs with undercuts | | |
| | <10° slope | 9 |
| | 10-20° slope | 9 |
| | 20-37° slope | 7 |
| | 37-45° slope | 7 |
| | >46° slope | 6 |
| Possibility to pass through water | | |
| | - of 0.0 - 0.4 m depth | 4 |
| Note: land to water transition zone poses more of a challenge than deeper conditions due to dynamics of pressure/depressure cycling. | | |
| Capability of sustaining hits | | |
| | From debris and small objects | 9 |
| | From hanguns | 7 |
| | From high velocity rounds (7.62) | 5 |

| | | TRL<br>TRL Code [1..9] |
|---|---|---|
| **Operational requirement** | | |
| | From RPG | 1 |
| Capability of operating and subsequent decontamination in hazardous environments | | |
| | Nuclear contamination | 7 |
| | Biological contamination | 4 |
| | Chemical contamination | 4 |
| | Fire | 4 |
| | Environmental (snow, sandstorms, high winds, electrical storms) | 4 |
| Capability of surviving a fall | | |
| | <1 mt | 9 |
| | 1 to 3 mt | 9 |
| | 3-10 mt | 5 |
| | >10 mt | 3 |
| EMC capabilities | | |
| | In urban environment (non EMC hostile) | 9 |
| | In battlefield environment | 4 |

*NOTES:*

*Height of obstacles to be cleared and speed should be expressed in terms of body units rather than in absolute values*

*Prevention of spotting in moving conditions (visible light) has been graded considering battlefield technology and not human eyesight.*

*Several points are highly dependent on size of the UGV and associated powerplant (i.e. Diesel engines vs. batteries operating in polar conditions)*

*The above analysis assumes that all the logistics and maintenance support will be comparable to other battle vehicles*

**POST SCENARIO ADD-ONS**

***CARRY EQUIPMENT FOR DISMOUNTED SOLDIER SCENARIO***

| | | |
|---|---|---|
| Payload capabilities | | |
| | <5 Kg | 9 |
| | 5-25 Kg | 9 |
| | 25-100 Kg | 7 |
| | 100 - 500 Kg | 5 |
| | > 500 Kg | 5 |

*NOTES TO THIS SCENARIO:*

*Size of UGV is to be specifically described by end user*

*Mission duration is to be given in order to assess TRL for UGV to be used*

*Safety aspects of navigation in this scenario are paramount and ought to be assessed by other teams*

***CONVOYING - TRANSPORT OF GOODS***

| | |
|---|---|
| Operator control interface (operator can take control of the UGV locally) | 9 |

*NOTES TO THIS SCENARIO:*

*Size of UGV is to be specifically described by end user*

*Mission duration is to be given in order to assess TRL for UGV to be used*

*Safety aspects of navigation in this scenario are paramount and ought to be assessed by other teams*

*Assessment has been made only from a platform point of view (not navigational or sensors)*

***CHECKING VEHICLES AND PEOPLE FOR EXPLOSIVES AT CHECKPOINTS***

| | |
|---|---|
| Capability of carrying manipulators and sensors | 9 |

| Operational requirement | | TRL<br>TRL Code [1..9] |
|---|---|---|
| Presence of an audible warning and communication system | | 9 |
| Capability of keeping vehicles and people from getting away | | |
| | Carrying a weapon to deter motion | 9 |
| | Activate associated checkpoint security measures | 5 |
| Capability of shielding explosions | | |
| | Activate associated checkpoint security measures | 5 |
| | Deploy UGV mounted screen | 5 |

*NOTES TO THIS SCENARIO:*

*Size of UGV is to be specifically described by end user*

*Mission duration is to be given in order to assess TRL for UGV to be used*

*Safety aspects of navigation in this scenario are paramount and ought to be assessed by other teams*

***DE-MINING (Tactical and Post-Conflict)***

*NOTES TO THIS SCENARIO:*

*Size of UGV is to be specifically described by end user*

*Mission duration is to be given in order to assess TRL for UGV to be used*

*Safety aspects of navigation in this scenario are paramount and ought to be assessed by other teams*

*Refer above for AP AT resistance*

*Speed should be specified being critical in tactical missions*

*Given that sensor technology is not ready, we suggest the use of a swarm of UGVs to increase the speed*

*If sensor technology will be ready in the future it will be possible to use a swinging arm to scan the front line avoiding obstacles (capability to scan not planar terrain fast enough)*

*It's almost impossible to sustain indirect fire from mortars*

*UGV are best suited in deforestation and vegetation removal tasks related to de-mining*

***RECON and SURVEILLANCE (NBC)***

## C.3 SENSING AND WORLD MODELLING

The TRL codes indicating the 2004 status for all sensing and world modelling related user requirements are shown in the table below.

| Operational requirement | TRL<br>TRL Code [1..9] |
|---|---|
| Usability vision systems under light conditions | |
| - Blazing sunshine | 9 |
| - Dense mist | 5 |
| - Darkness | 9 |
| - Snow on the ground (currently not snowing) | 9 |
| Usability vision systems under precipitation conditions | |
| - Light rain | 9 |
| - Heavy rain | 1 |
| - Light snowing | 9 |
| - Heavy snowing | 1 |
| Possibility to observe up to 90 degrees around | |
| - in vertical sector with lower boundary of < -15 degrees | 9 |

| | TRL |
|---|---|
| | TRL Code [1..9] |
| **Operational requirement** | |
| - in vertical sector with lower boundary of -15..-10 degrees | 9 |
| - in vertical sector with lower boundary of -10..-5 degrees | 9 |
| - in vertical sector with lower boundary of -5..0 degrees | 9 |
| - in vertical sector with lower boundary of 0 degrees | 9 |
| - in vertical sector with lower boundary of > 0 degrees | 9 |
| - in vertical sector met upper boundary of < 0 degrees | 9 |
| - in vertical sector met upper boundary of 0..15 degrees | 9 |
| - in vertical sector met upper boundary of 15..30 degrees | 9 |
| - in vertical sector met upper boundary of > 30 degrees | 9 |
| Possibility to observe up to 120 degrees around | |
| - in vertical sector with lower boundary of < -15 degrees | 9 |
| - in vertical sector with lower boundary of -15..-10 degrees | 9 |
| - in vertical sector with lower boundary of -10..-5 degrees | 9 |
| - in vertical sector with lower boundary of -5..0 degrees | 9 |
| - in vertical sector with lower boundary of 0 degrees | 9 |
| - in vertical sector with lower boundary of > 0 degrees | 9 |
| - in vertical sector met upper boundary of < 0 degrees | 9 |
| - in vertical sector met upper boundary of 0..15 degrees | 9 |
| - in vertical sector met upper boundary of 15..30 degrees | 9 |
| - in vertical sector met upper boundary of > 30 degrees | 9 |
| Possibility of autonomous obstacle avoidance on commanded routes | |
| - of pit holes of < 1 m wide and < 1 m long | 7 |
| - of water pools in road of < 1 m wide and < 1 m long | 4 |
| - of vegetation (bushes) on road of < 1 m high and < 0.5 m wide | 7 |
| - of stones and/or metal on road of < 1 m high and < 0.5 m wide | 7 |
| Possibility to detect Anti Personnel (AP) mines | |
| - chance of not detecting a present AP mine < 1% | 2 |
| - chance of not detecting a present AP mine 1..5% | 2 |
| - chance of not detecting a present AP mine 5..10% | 3 |
| - chance of not detecting a present AP mine >10% | 4 |
| - chance of falsely detecting a non-present AP mine < 1% | 2 |
| - chance of falsely detecting a non-present AP mine 1..5% | 2 |
| - chance of falsely detecting a non-present AP mine 5..10% | 3 |
| - detection width < 3 m | 9 |
| - detection width 3..5 m | 9 |
| - detection width > 5 m | 9 |
| - detection AP mine on surface | 7 |
| - detection AP mine at 1..10 cm depth | 5 |
| - detection AP mine at > 10 cm depth | 2 |
| Possibility to detect Anti Tank (AT) mines | |
| - chance of not detecting a present AT mine < 1% | 3 |
| - chance of not detecting a present AT mine 1..5% | 3 |
| - chance of not detecting a present AT mine 5..10% | 4 |
| - chance of not detecting a present AT mine >10% | 5 |
| - chance of falsely detecting a non-present AT mine < 1% | 3 |
| - chance of falsely detecting a non-present AT mine 1..5% | 3 |
| - chance of falsely detecting a non-present AT mine 5..10% | 4 |
| - detection width < 3 m | 9 |

| | TRL |
|---|---|
| | TRL Code [1..9] |
| **Operational requirement** | |
| - detection width 3..5 m | 9 |
| - detection width > 5 m | 9 |
| - detection AT mine on surface | 8 |
| - detection AT mine at 1..10 cm depth | 6 |
| - detection AT mine at > 10 cm depth | 3 |
| Possibility to autonomously generate firing request (but no autonomous firing by the UGV itself) | 8 |
| Possibility to detect (i.e. see that it is there) targets under average visibility circumstances | |
| - alighted personnel at distances > 500 m | 9 |
| - alighted personnel at distances > 1000 m | 9 |
| - alighted personnel at distances > 1500 m | 9 |
| - individual vehicles at distances >1000 m | 9 |
| - individual vehicles at distances > 2000 m | 9 |
| - individual vehicles at distances > 3000 m | 9 |
| Possibility to recognize (i.e. see what it is) targets under average visibility circumstances | |
| - alighted personnel at distances > 500 m | 9 |
| - alighted personnel at distances > 1000 m | 9 |
| - alighted personnel at distances > 1500 m | 9 |
| - individual vehicles at distances >1000 m | 9 |
| - individual vehicles at distances > 2000 m | 9 |
| - individual vehicles at distances > 3000 m | 9 |
| Possibility to identify (i.e. see who it is) targets under average visibility circumstances | |
| - alighted personnel at distances > 500 m | 7 |
| - alighted personnel at distances > 1000 m | 6 |
| - alighted personnel at distances > 1500 m | 6 |
| - individual vehicles at distances >1000 m | 8 |
| - individual vehicles at distances > 2000 m | 7 |
| - individual vehicles at distances > 3000 m | 6 |
| Possibility to detect (i.e. see that it is there) targets under less visibility circumstances | |
| - alighted personnel at distances >100 m | |
| - alighted personnel at distances > 250 m | |
| - alighted personnel at distances > 500 m | |
| - individual vehicles at distances >1000 m | |
| - individual vehicles at distances > 2000 m | |
| - individual vehicles at distances > 3000 m | |
| Possibility to recognize (i.e. see what it is) targets under less visibility circumstances | |
| - alighted personnel at distances >50 m | |
| - alighted personnel at distances > 100 m | |
| - alighted personnel at distances > 250 m | |
| - individual vehicles at distances >1000 m | |
| - individual vehicles at distances > 2000 m | |
| - individual vehicles at distances > 3000 m | |
| Possibility to identify (i.e. see who it is) targets under less visibility circumstances | |
| - alighted personnel at distances > 50 m | |
| - alighted personnel at distances > 100 m | |
| - alighted personnel at distances > 250 m | |
| - individual vehicles at distances >1000 m | |
| - individual vehicles at distances > 2000 m | |
| - individual vehicles at distances > 3000 m | |

| | TRL |
|---|---|
| | **TRL Code [1..9]** |
| **Operational requirement** | |
| Possibility to follow moving targets | |
| - at target moving speed of < 20 km/h | 9 |
| - at target moving speed of 20..50 km/h | 9 |
| - at target moving speed of 50..100 km/h | 9 |
| - at target moving speed of > 100 km/h | 9 |
| - at viewing angle change speed < 5 degrees/s | 9 |
| - at viewing angle change speed 5..15 degrees/s | 9 |
| - at viewing angle change speed 15..30 degrees/s | 9 |
| - at viewing angle change speed > 30 degrees/s | 9 |
| Radar sensing has different operational requirements | |
| detection | 9 |
| recognition | 7 |
| identification | 5 |
| tracking | 9 |
| Acoustic sensing has different operational requirements | |
| detection | 9 |
| recognition | 6 |
| identification | 5 |
| tracking | 9 |
| CE Obstacle classification (avoidance & negotiation) | |
| flat surfaces, rural roads | 9 |
| smooth hilly terrain | 6 |
| rocky terrain | 5 |
| forests | 4 |
| inside houses - manmade constructions | 0 |
| CarryEq Tracking soldier | |
| flat surfaces, rural roads | 9 |
| smooth hilly terrain | 7 |
| rocky terrain | 4 |
| forests | 4 |
| CE Terrain modelling | |
| geometry sensing | 7 |
| terrain classification (surface conditions) | 3 |
| CE Sense group splitting | 7 |
| CE manoeuvre covertly (sense cover) | 4 |
| Detect explosives (suspect materials-packages) | |
| at 5 m | 4 |
| at 0.1 m | 7 |
| Identify explosives | |
| at 5 m | 2 |
| at 0.1 m | 6 |
| Sense environment for shielding | 7 |
| Detect persons in vehicles | 9 |
| Transport in normal traffic | |
| paved roads | 8 |
| rural-dirt roads | 7 |
| unstructured terrain | 6 |
| heavy traffic | 7 |

| | TRL |
|---|---|
| | **TRL Code [1..9]** |
| **Operational requirement** | |
| Following another vehicle | |
| same vehicle | 9 |
| other vehicle - motorbike | 7 |
| Traffic sign recognition | 7 |
| Detect mine surface AP 1% detection | |
| road | 8 |
| flat field low vegetation | 6 |
| forests | 4 |
| hilly terrain | 3 |
| rocky terrain | 2 |
| Detect mine surface AT | |
| road | 9 |
| flat field low vegetation | 7 |
| forests | 5 |
| hilly terrain | 4 |
| rocky terrain | 3 |
| Detect mine buried AP | |
| road | 4 |
| flat field low vegetation | 3 |
| forests | 1 |
| hilly terrain | 1 |
| rocky terrain | 1 |
| Detect mine buried AT | |
| road | 5 |
| flat field low vegetation | 4 |
| forests | 2 |
| hilly terrain | 2 |
| rocky terrain | 2 |
| Maintain database of persons and vehicles (location & motion) average visibility - open terrain | |
| range 50 m | 9 |
| range 200 m | 8 |
| range 1000 m | 5 |
| Detect Nuclear contamination | |
| contact | 9 |
| standoff 1km | 1 |
| Detect chemical contamination | |
| contact | 9 |
| standoff 1km | 5 |
| Detect biological contamination | |
| contact | 6 |
| standoff 1km | 3 |
| Environment mapping at sensor range | |
| routes | 7 |
| traffic | 8 |
| buildings | 7 |
| route state positive obstacles | 7 |
| route state negative obstacles | 1 |

## C.4 NAVIGATION AND MISSION PLANNING

The TRL codes indicating the 2004 status for all navigation and mission planning related user requirements are shown in the table below.

| | TRL |
|---|---|
| | TRL Code [1..9] |
| **Operational requirement** | |
| Possibility of alternative routes if the commanded route does not work | |
| - autonomous alternative route determination | 6 |
| - fully manual alternative route determination by the operator | 8 |
| - autonomous alternative route determination, with possibility for the operator to overrule | 6 |
| Possibility to follow roads | |
| - dirt road | 6 |
| - brick road | 6 |
| - asphalt road | 7 |
| Possibility to follow vehicles (convoy) | |
| - leader vehicle can be specific type only (e.g. possibility to follow specific military vehicle type only) | 8 |
| - leader vehicle can be any type (e.g. possibility to follow any civil or military vehicle type that is available) | 5 |
| - leader vehicle that is man driven | 8 |
| - leader vehicle that is autonomous | 7 |
| Possibility to drive in mixed traffic (UGV within normal traffic) | |
| - at < 5 km/h | 7 |
| - at 5..20 km/h | 6 |
| - at 20..50 km/h | 5 |
| - at 50..70 km/h | 4 |
| - at > 70 km/h | 3 |
| Possibility to drive in crowed streets (urban terrain) | 5 |
| Possibility to autonomously navigate along a route with maximum cover | 3 |
| Possibility to autonomously navigate along a route avoiding hostile fire | 2 |
| Possibility to autonomously navigate through vegetation | |
| - high grass | 6 |
| - sparse bushes of < 0.5 m high | 6 |
| - sparse bushes of < 1 m high | 6 |
| - sparse bushes of > 1 m high | 6 |
| - dense bushes of < 0.5 m high | 6 |
| - dense bushes of < 1 m high | 6 |
| - dense bushes of > 1 m high | 6 |
| Possibility of alternative routes if the commanded route does not work | |
| - autonomous alternative route determination on roads (database available) | 9 |
| Need for mission planning capabilities | |
| Possibility to detect roads under all weather conditions /day & night | |
| Need for situation awareness | |
| Possibility to follow vehicles (convoy); leader vehicle can be any type | |
| - leader vehicle that is man driven | 5 |
| - leader vehicle that is autonomous | 5 |

## C.5 HUMAN-ROBOT INTERACTION

The TRL codes indicating the 2004 status for all human-robot interaction related user requirements are shown in the table below.

| | TRL<br>TRL Code<br>[1..9] |
|---|---|
| **Operational requirement** | |
| Initial training effort required for mastering basic UGV control for non-expert. | |
| < 1 hour | 2 |
| < 8 hours | 9 |
| < 1 week | 9 |
| < 2 weeks | 9 |
| < 1 month | 9 |
| Training effort required for basic UGV control for trained personnel to maintain required skill level | |
| < 1 hour per month | 9 |
| < 1 hour per week | 9 |
| < 8 hours per month | 9 |
| < 8 hours per week | 9 |
| Workload/Occupation level for operator performing basic UGV control in simple terrain | |
| < 25 % | 2 |
| < 50 % | 3 |
| < 75 % | 4 |
| Workload/Occupation level for operator performing basic UGV control in difficult terrain | |
| < 25 % | 1 |
| < 50 % | 1 |
| < 75 % | 2 |
| Possibility to substitute/support UGV operator training/instructing using interactive simulations | |
| - for basic UGV control and maneuvering | 7 |
| - for payload related control | 5 |
| Possibility to evaluate the performance of the human-robot team | 4 |
| Possibility to define measures of effectiveness for the human-robot team | 5 |
| Possibility of consistent interface design for different UGVs for common UGV functions (on/off, maneuvering, parking etc.) | |
| - standardized controls (e.g. Maneuvering) | 7 |
| - standardized symbolic representation (e.g. ISO, DIN, MIL based symbols) | 2 |
| - standardized layout or sub-layouts for interface components | 1 |
| Possibility to integrate user interface into existing IT equipment | |
| - integration into existing equipment | |
| - integration into planned equipment | |
| Possibility to provide robot execution plan to operator | |
| - ahead of mission | 4 |
| - ahead of maneuver | 4 |
| - in real time (online) | 7 |
| - after execution | 8 |
| Possibility to estimate/measure/predict UGV performance | |
| - ahead of mission | 3 |
| - ahead of maneuver | 4 |
| - in real time (online) | 4 |
| - after execution | 6 |
| Possibility to share UGV control between multiple operators | 4 |
| Possibility to have one operator control multiple UGVs in a serial setting (only one UGV active at a time) | |
| # 2 | 2 |
| # 4 | 1 |
| # 6 | 1 |
| # 8 | 1 |

| Operational requirement | TRL Code [1..9] |
|---|---|
| Possibility to have one operator control multiple UGVs in a concurrent setting (all UGVs can be active) | |
| # 2 | 2 |
| # 4 | 1 |
| # 6 | 1 |
| # 8 | 1 |
| Possibility to scale operator to robot ratio on demand (adapting to unexpected workload peaks) | 1 |
| Possibility to integrate UGV and payload control into a single operator interface | 3 |
| Interaction limitations caused by UGV loosing line of sight (LOS) contact with operator | |
| - no limitations | |
| - LOS functionality replaced/covered by redundant non-LOS functions | |
| - LOS functionality partially replaced by non-LOS functions | |
| - loss of LOS functionality | |
| Levels of mobility for control station having at least an 800x600 color display and pointing and text entering capability | |
| - stationary installation | 9 |
| - vehicle based installation | 9 |
| - vehicle based, can be used while vehicle is moving | 4 |
| - stationary but man-portable | 9 |
| - wearable, requiring an operator to interrupt other activities (e.g. Moving) | 4 |
| - wearable, can be used while performing other activities (e.g. Head-mounted display, voice controlled) | 2 |
| Required setup time until operational for control station having at least an 800x600 color display and pointing and text entering capability | |
| - always on, mobile, no setup time required | |
| - minimal setup time (e.g. Boot time) | |
| < 1 minute | |
| < 30 minutes | |
| < 1 hour | |
| Degradation of performance (e.g. speed, accuracy) for basic UGV control when operator is wearing protective gloves | |
| - no degradation | |
| < 25 % | |
| < 50 % | |
| < 75 % | |
| Degradation of performance (e.g. speed, accuracy) for basic UGV control when operator is wearing protective vest | |
| - no degradation | |
| < 25 % | |
| < 50 % | |
| < 75 % | |
| Degradation of performance (e.g. speed, accuracy) for basic UGV control when operator is wearing full ABC protection | |
| - no degradation | |
| < 25 % | |
| < 50 % | |
| < 75 % | |
| Achievable level of precision in simple terrain for entering/modifying commands within 10m radius of robot | |
| < 0.01m | 9 |
| < 0.1m | 9 |
| < 0.5m | 9 |
| < 1m | 9 |

| Operational requirement | TRL Code [1..9] |
|---|---|
| Achievable level of precision in simple terrain for entering/modifying commands within 50m radius of robot | |
| < 0.01m | 9 |
| < 0.1m | 9 |
| < 0.5m | 9 |
| < 1m | 9 |
| < 5m | 9 |
| Possibility to realise mobile human robot interface using COTS products (e.g. Laptops, Joysticks, Batteries, etc.) | 9 |
| Possibility to add, modify or delete elements of the UGVs internal world representation | 3 |
| Possibility to interact deviceless with robot (e.g. Pointing gestures) | 2 |
| Possibility to provide robot command interpretation feedback to enable online command verification | 5 |
| Possibility to provide robot command execution projection to enable online command execution supervision | 5 |
| Possibility to create/edit/delete waypoints | 7 |
| Initial training effort required for mastering basic UGV control for non-expert.{Agent based Systems) | |
| < 1 hour | 1 |
| < 8 hours | 1 |
| < 1 week | 2 |
| < 2 weeks | 2 |
| < 1 month | 3 |
| Initial training effort required for mastering basic UGV control for non-expert. | |
| < 4 hour | 6 |
| Possibility to provide robot execution plan to operator | |
| ahead of maneuver (emerging behaviour) | 2 |
| in real time emerging behaviour (online) | 2 |

## C.6 MULTI-ROBOT SYSTEMS

The TRL codes indicating the 2004 status for all multi-robot systems related user requirements are shown in the table below.

| Operational requirement | TRL Code [1..9] |
|---|---|
| Possibility to interact with other robots | |
| - exchange map information between UGV's | 9 |
| - exchange target observation information between UGV's | 9 |
| - perform a task with multiple, collaborative UGV's | 4 |
| - autonomously divide a task, specified by the operator, between several UGV's | 2 |
| - interact with other UGV's performing exactly the same task | 4 |
| - interact with other UGV's performing different, specialised tasks | 2 |
| Organisation of the robot groups | |
| should there be a group leader | |
| System of the robot group | |
| should the system have a completely decentralized infrastructure | |
| should the system have a centralized infrastructure | |
| should the system have a hierarchical infrastructure | |
| Level of task coverage (redundance with the robot group regarding the robot group task) | |
| Low (very individual robots, specialists) | |

| | TRL |
|---|---|
| | **TRL Code [1..9]** |
| **Operational requirement** | |
| medium | |
| high (all the robots are more or less the same) | |
| Possibility to establish and maintain a formation | |
| ability to implement initial mission plan | 6 |
| ability to follow change of mission plan | 3 |
| ability to replan because of failures or changes in the environment | 2 |
| Possibility to establish ad hoc communication between robots | 7 |
| Cooperative Perception | |
| ability to share data from multiple sources | 5 |
| collectively recognize objects of interest | 2 |
| provide estimates of position bearing | 3 |
| Ability to validate and verify for functionality, reliability, and safety | 1 |
| Possibility to provide a dedicated user interface for multi-robot supervision | 3 |
| Ability to manage and to prioritize events | 3 |

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| Design | Obstacle avoidance | Signal processing |
| Ground vehicles | Obstacle detection | Specifications |
| Land mine detection | Operations research | Systems analysis |
| Mechanical properties | Prototypes | Systems engineering |
| Military applications | Remotely operated vehicles | |

**14. Abstract**

There appears to exist a gap between the ideas of the military on the use of ground robotics for their purposes and the technical possibilities offered by industry and research. In many cases the military are offered robots created by industry, but to a lesser degree robots developed to explicitly meet military needs.

To bridge this gap, a NATO workshop was organised September 2004 in Bonn, attended by over 70 participants from the military, industry, research and ministries from 16 different mainly European countries. The starting point for the workshop was defining the tasks for which the military would most like to use robots by the year 2008, including the functional requirements. In parallel, the industry and researchers defined the current status of robotics technology and the level of technology that is expected to be achieved by the year 2008 at the current rate of technology development.

Based on the differences between military needs on one hand and the expected level of technology by 2008 on the other hand, roadmaps were constructed. These roadmaps identify which actions should be taken in order to achieve the required level of technology by 2008, if at all possible. They also identify who should take action and how this should be organised.

It was recognised during the workshop that this is the first time that this type of analysis on the gap between user requirements and technical possibilities has been attempted.

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Holargos, Athens

**HONGRIE**
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Institute of Military Technology
Ministry of Defence
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